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**NAVAL
POSTGRADUATE
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MONTEREY, CALIFORNIA

THESIS

NPS-SCAT; ELECTRICAL POWER SYSTEM

by

Lawrence Tyrone Dorn Jr.

September 2009

Thesis Advisor:	James H. Newman
Second Reader:	James A. Horning

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NPS-SCAT; ELECTRICAL POWER SYSTEM

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN SPACE SYSTEMS OPERATIONS

from the

**NAVAL POSTGRADUATE SCHOOL
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ABSTRACT

The Naval Postgraduate School Solar Cell Array Tester (NPS-SCAT) seeks to expand the CubeSat knowledge base and provide learning possibilities at the Naval Postgraduate School. This thesis discusses the design, testing, and integration of the electrical power sub-system for NPS-SCAT. The current design will be powered by a commercial off-the-shelf power system developed by Clyde Space systems. Solar power generation will be via Spectrolab's improved triple junction solar cells. Satellite Tool Kit (STK) was used to approximate the expected power generation and communication periods while on orbit. The design, building and integration and testing of the solar panels using NuSil adhesive tape will also be discussed. Finally, the operational limits imposed on SCAT operations, due to load and power generation capabilities of the electrical power system, will also be discussed.

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I. INTRODUCTION

A. THE GROWTH OF THE CUBESAT COMMUNITY

The CubeSat concept was first developed by Stanford University and California Polytechnic State Institute, San Luis Obispo (Cal Poly) in 1999, in hopes of developing greater student opportunities for satellite development curricula.¹ Since then, the CubeSat community has shown steady growth through out the world with the first successful CubeSat launches occurring on 30 June 2003. The first launch consisted of six CubeSats deployed from the Cal Poly designed Poly-Picosatellite orbital deployer (P-Pod).² The P-Pod is designed to carry up to three 1U CubeSats. The 1U standard is a cube sized satellite with a max dimension of 10 cm x 10 cm x 10 cm and a maximum weight of approximately 1 kg. 2U and 3U units are also possible to allow for increased payload capabilities.

As the active CubeSat community increases in both the educational and commercial realms, Cal Poly continues to provide the lead in maintaining CubeSat standards, education, ground station networking and coordination of launch opportunities for CubeSat designers and educational institutions.³ Prominent members in the United States space community have come together to form the CubeSat Standards

¹ C.S. Malone, "NPS Solar Cell Array Tester: A Project Managers Perspective." Monterey: Naval Postgraduate School thesis, 2009.

² Lori Brooks, "CubeSat History" (brief presented at CubeSat Developers Summer Workshop 2007).

³ C.S. Malone, "NPS Solar Cell Array Tester: A Project Managers Perspective." Monterey: Naval Postgraduate School thesis, 2009.

Committee. The current members of the committee are Cal Poly, NASA, United Launch Alliance, Orbital Science, Space X, the Office for Responsive Space, and the National Reconnaissance Office.⁴

B. THE NAVAL POSTGRADUATE SCHOOL SMALL SATELLITE PROGRAM

The Naval Postgraduate School's first satellite, Petite Amateur Navy Satellite (PANSAT), was conceived in March 1989 and launched in October 1998. The newest satellite construction being undertaken is the Naval Postgraduate School (NPS) Spacecraft Architecture and Technology Demonstration Satellite (NPSAT1). The concept was approved for construction 1999, and has a preliminary launch expectation for a 2012 launch. Both of these satellites have provided enhanced educational and professional growth of student military officers in the Space Systems Curriculums at NPS.⁵

C. THE NAVAL POSTGRADUATE SCHOOL CUBESAT PROGRAM

The NPS adoption of the CubeSat standard allows for a significant increase in the educational opportunities for the students and faculty. The small form factor and the ability to rapidly design and build CubeSats from kits and COTS components at a fraction of the cost of larger satellites, makes CubeSats perfect for the space student educational pipeline. As the form factor standards allow for

⁴ C. S. Malone, "NPS Solar Cell Array Tester: A Project Manager's Perspective." Monterey: Naval Postgraduate School thesis, 2009.

⁵ M.P. Schroer, NPS-SCAT: A Cubesat Communications System Design, Test, and Intergration. Monterey: Naval Postgraduate School thesis, 2009.

different size CubeSat, the units can be as simple or complex as the builder wishes. With CubeSat designs that allow for rapid building, it is possible for the student to see the complete satellite lifespan from concept, construction, testing, launch and operation. The NPS Solar Cell Array Tester (NPS-SCAT) is the first CubeSat project to be undertaken at NPS.

The SCAT mission is to validate solar cell performance while in the space environment over the life of the satellite. SCAT will utilize commercial-off-the-shelf (COTS) components wherever possible. Each subsystem will be interoperable with the CubeSat standards. The component selection is discussed in Chapter II.

NPS student and faculty presented the proposed SCAT program to the Department of Defense (DoD) Space Experiments Review Board (SERB) in October 2008. The SCAT program was approved for space flight along with four other NPS space experiments.

SCAT design parameters are located in Table 1. Figure 1 shows the initial design concept of the SCAT CubeSat with the Solar cell measurement system located on the top of the CubeSat.

Design Life:	12-18 months
Altitude	~410km
Inclination	51.6°
Launch Vehicle	Space Shuttle STS - SSPL-5510 EELV - PPOD
Survivability	Susceptible to Natural Environment
Primary Telemetry, Tracking & Control:	ISM Band transceiver
Secondary TT&C:	Amateur Band Transceiver Beacon
Regulations:	Frequency Allocation Experimental license and Amateur Band in the Clear
Schedule:	Complete Construction for Testing December 2009
Components	COTS as Available, Nano-Satellite/CubeSat-Class interfaces within Program budget
Volume/Mass:	10cm x 10cm x10cm Subsystems Limited to CubeSat Class Components
Power Generation:	Limited to CubeSat-Class Components (~1.5W peak)

Table 1. SCAT Design Constraints

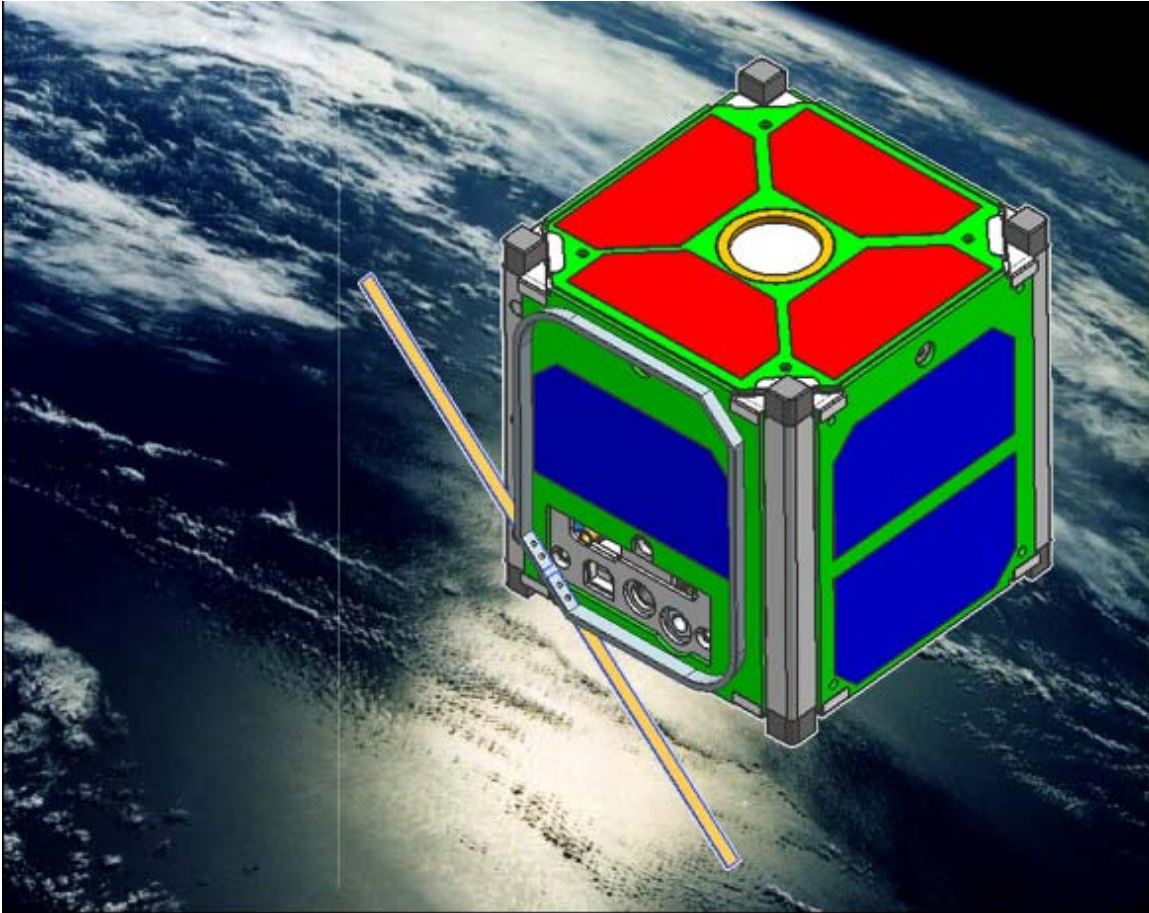


Figure 1. SCAT on Orbit

D. A BRIEF HISTORY AND FUTURE OF CUBESAT POWER SYSTEMS

CubeSat power systems up until now have been relatively small and uncomplicated. As the only real standards for the CubeSat are the external dimensions and weight limits, the complexity or simplicity of power systems is left up to the user. Pumpkin has designed an integrated power supply for user CubeSat development. Currently, there are two commercial companies that provide CubeSat power supplies, Clyde Space and GOMspace. For the SCAT project, the Clyde Space option was selected.

While the use of COTS can be used for rapid CubeSat construction, there are limitations of using a commercial electrical power system (EPS). Limitations including the lack of documentation on the EPS true operational parameters. Lack of adequate schematic diagrams make it difficult to understand how to fully integrate the EPS with CubeSat subsystems or the ability to troubleshoot the EPS as required.

As the launch and delivery methods of CubeSats increase through projects like the Naval Postgraduate School CubeSat Launcher (NPSCuL), the CubeSat can increase in size. 3U and larger may become common depending on launch capabilities. As CubeSats get larger, the power generation and complexity of the EPS will become greater and more complex to support the multitude of subsystems that can be incorporated within the larger CubeSat size; however, the educational intent of the smaller 1U sizes should remain dominate with the larger CubeSat sizes being developed by bigger commercial developers.

II. SOLAR CELL ARRAY TESTER POWER SYSTEM REQUIREMENTS

A. SUBSYSTEMS DESCRIPTIONS AND POWER REQUIREMENTS

1. Communications Systems

Telemetry, tracking, and command (TT&C) system on SCAT will consist of two communication pathways, a high bandwidth and a low bandwidth pathway. Both communication pathways will be capable of transmitting SCAT data back to the ground station. The primary high bandwidth communications channel will be via a commercial Microhard radio on the industrial, scientific and medical (ISM) 2.4 GHz band. The secondary pathway will be through a radio beacon on the 436 MHz amateur radio frequency band.⁶

a. *Microhard 2400*

The 2400 radio was selected, as it is CubeSat compatible and has flown on previous CubeSats.^{7,8} MHX 2400 specifications are listed in Table 2; however, actual testing and measurement of the power consumed by the MHX 2400 radio was ~4 Watts during transmission, and ~1.25 Watts in receive mode.

⁶ Ortiona et al., "The Naval Postgraduate School SCATT++ CubeSat Program." 4, 2009.

⁷ B. Klofas, & J. Anderson, "A Survey of CubeSat Communication Systems," 2008.
http://atl.calpoly.edu/~bklofas/Presentations/DevelopersWorkshop2008/ComSurvey-Bryan_Klofas.pdf.

⁸ Ortiona et al., "The Naval Postgraduate School SCATT++ CubeSat Program." 4, 2009.

Parameter	Value
Band	2.4 GHz Ism
Transmission Method	Freq. Hopping Spread Spectrum
Serial Data Rate	up to 115 Kbps
RF Output Power	up to 1 W, selectable
power Consumption (Rx/Tx)	1.15 W / 4.38 W
Sensitivity (@25° C)	- 105 dBm
Max. Throughput	83 kbps (no delay)
Weight	75 grams
Size	90 mm x 53 mm x 25 mm

Table 2. MHX 2400 Specifications⁹

b. Communications Beacon

The communications beacon for SCAT will be used as the secondary communication path. It will be able to transmit abbreviated SCAT operating parameters and limited I-V curve data. It will also allow for resetting of the CubeSat on a malfunction of the operating software. The beacon has been designed by Cal Poly. The beacon is constrained to 436 MHz +/- 2 MHz. The Beacons effective isotropic radiated power (EIRP) is approximately +33 dBm or less with a frequency shift keying (FSK) bandwidth of less than 5 kHz. Emission type is 1200 baud FSK AX.25 with a 5 word per minute continuous wave (CW) preamble. Antenna pattern is very similar to a standard ¼ wave dipole. As power consumption of the beacon is unknown, a conservative estimate of 1 Watt will be used for power calculations.

c. Microhard 2420

The Microhard 2420 radio was initially selected for the SCAT project as the manufacturer had stopped

⁹ I.A. Mas & C.A Kitts, "A Flight-proven 2.4 Ghz ISM Band COTS Communications System for Small Satellites," 21st AIAA/USU Conference on Small Satellites, Logan, Utah: AIAA, 2007.

production of the 2400 unit. Communication testing of the 2420 unit initially showed great promise. Data rates that would easily support SCAT communication requirements were achieved. Unfortunately, upon power consumption testing, it was discovered that the 2420 unit consumed significantly more power than indicated from the manufacturers' specifications. The testing of the unit showed power draw of over 13 W on the +5 V supply during transmission in the 1 W transmission mode. This power level was significantly higher than could be supplied by the Clyde Space EPS maximum of 6 W on the +5 V supply. After discussions with the manufacturer, the manufacturer agreed to produce, in limited quantities, the 2400 unit to support CubeSat projects. The use of the 2420 radio was postponed for CubeSats with greater power capabilities, but a number of lessons learned were gained.

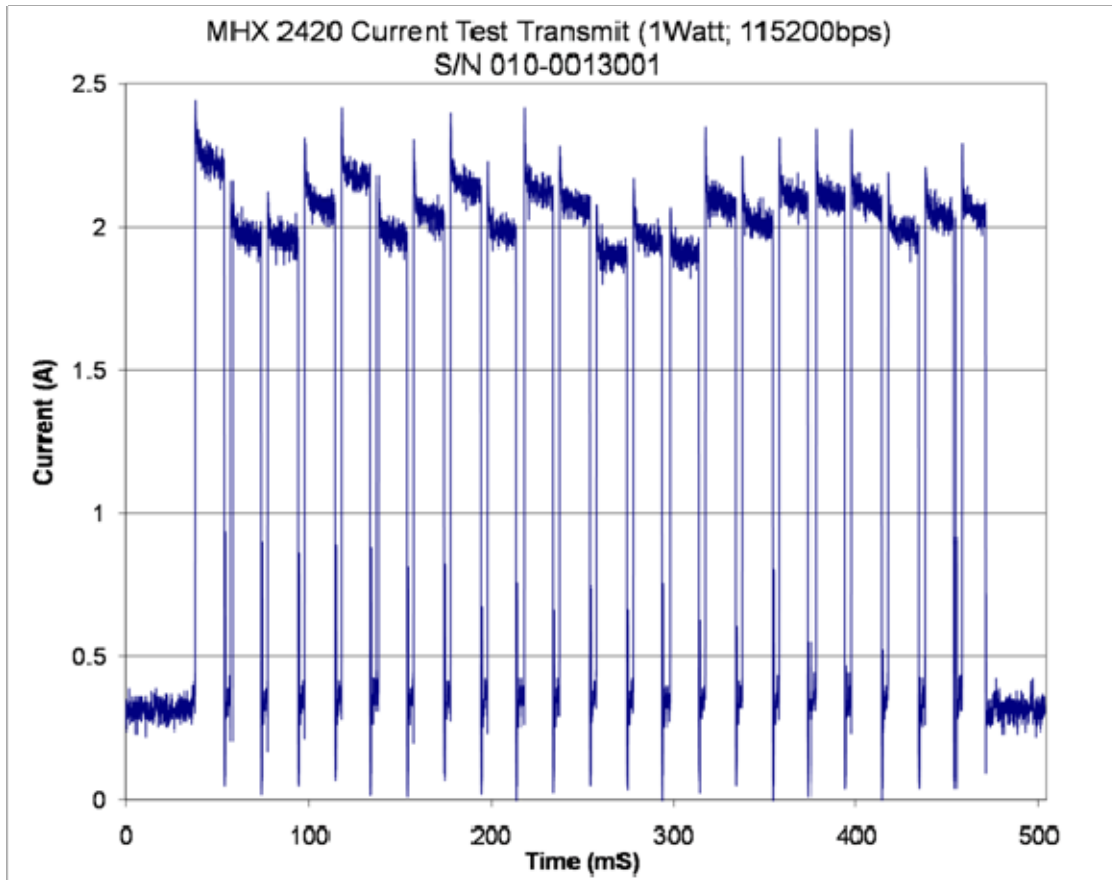


Figure 2. MHX 2420 Current Test Transmit 5V input power(1 Watt; 115200 bps)(From Schroer, 2009)

2. Solar Measurement System, Sun Sensor and Temperature Sensors

The primary experimental payload of the SCAT satellite is the Solar Cell Measurement System (SMS). The SMS design had already been designed for the previous NPS NPSAT1. The SCAT system will consist of different experimental solar cells, temperature sensors, a sun sensor, and circuitry modified to be compatible with the CubeSat design. The experimental solar cells, temperature sensors and a sun sensor will be on plus Z face of the satellite as show in Figure 1. Periodically during an orbit, the circuitry will

measure each experimental solar cell current as a function of voltage along with the temperature and incident sun angle on the cells.¹⁰ An example output of the SMS is shown in Figure 3.

Operational power testing of the complete SMS module, including sun sensor and temperature sensors showed low power consumption. The SMS consumed 294 mW while actively taking Solar I-V curves and a minimal 67 mW while in standby operations.

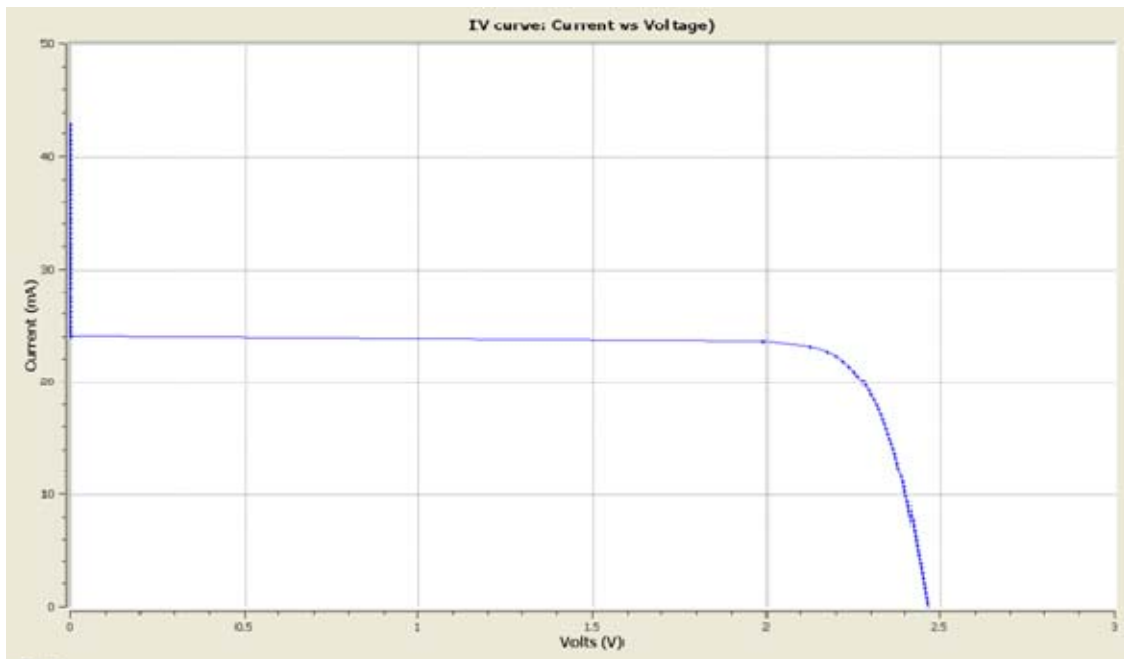


Figure 3. SMS I-V curve example

3. FM430 Flight Module

The Pumpkin FM430 flight module is the SCAT's main processor, and is based on Texas Instruments MSP430 series of ultra low power microcontrollers. All commands and

¹⁰ Ortiona et al., "The Naval Postgraduate School SCAT++ CubeSat Program." 6, 2009.

telemetry generated within the satellite will be sent to the FM430 for processing and external transmission as required.¹¹ The SCAT operating system program is written in ANSI C and makes use of Salvo, an event-driven cooperative multitasking real-time operating system (RTOS). The processor is able to communicate with the subsystems via serial peripheral interface (SPI) protocol and the Inter-Integrated Circuit interface I²C.¹² Power usage by the FM430 is very small at 10 mW.

4. Clyde-Space 1U Electrical Power Subsystem

a. General Description

The SCAT power system was selected with the goal of using COTS. Use of COTS hardware should allow for rapid integration of CubeSat designs, while maximizing educational opportunities for NPS students. As CubeSat component suppliers are still growing, there were only two COTS EPS that were considered for SCAT, Clyde Space and GOM Space. After a review of available products, the Clyde Space EPS was selected based on three major considerations. One, the Clyde Space unit had been flown on a previous CubeSat. GOM Space had not flown. Two, the initial estimates of power requirements for the proposed SCAT components were within the power handling capability of both units. Three, at the time of the EPS reviews, the specification differences between the GOM Space and Clyde Space units were not significant enough to choose one over the other. However,

¹¹ Ortiona et al., "The Naval Postgraduate School SCAT++ CubeSat Program." 7, 2009.

¹² Ibid.

since the EPS selection decision, GOM Space has upgraded their CubeSat EPS. It now provides more capabilities and power handling than the Clyde Space units. It also uses lithium ion batteries vice lithium poly batteries, lithium poly batteries having more safety and handling requirements than Lithium ion cells. After working with the Clyde Space unit and having to make a choice between the two units again, the choice would have been to go with the GOM Space unit vice Clyde Space unit.

The Clyde Space EPS is a self-contained, independent, and self-regulating power unit. The power supply can provide up to 6 Watts and 3.3 Watts of continuous power at 5 Volts and 3.3 Volts, respectively. The Clyde Space EPS 1.25 Amp-hour battery was also selected for use within the satellite. Two lithium polymer battery cells are wired in series to provide approximately 10 Watt-hours of energy at approximately 8 Volts. The SCAT fail-safe designed software programming will secure loads to prevent a complete discharge of the system when available power is insufficient to support system loads.

b. EPS Efficiency

The EPS documentation indicates 90% solar charge efficiency. This was consistent with EPS tests. The efficiency of the 5 V and 3.3 V regulators is not given. However, it was discovered in testing that the efficiency ranges from 61% to 80% based on load. The 5 V bus ranged from 77% to 80% efficient. The 3.3 V bus ranged from 61% to 77% efficient. Although the efficiency of the 3.3 V bus is low, there is very little current supplied from the 3.3 V bus. The FM430 being the only significant load on the 3.3 V

bus. These inefficiencies will be taken into account when the power budget is calculated by increasing the component measured power consumption by a bus inefficiency factor to give true power draw on the system battery.

c. Solar Cell Selection

The solar cells selected for power generation are Spectrolab Improved Triple Junction (ITJ) solar cells.¹³ The ITJ cells are rated at 26.8% efficient at beginning of life (BOL). Each ITJ cell has an area of 0.002667 m². This would allow a theoretical power generation of 0.971 W per cell. Initial power estimates were based on the use of eight ITJ cells for SCAT. However, it was later discovered that the Clyde Space EPS is unable to process solar arrays with less than 3.5 V output. Thus, the design of the solar panels was changed to allow three panels with two ITJ cells and two panels that contained eight Triangular Array Solar Cells (TASC). The TASC cells are more efficient at 28.3%. Each TASC cell has an area of 0.0002435 m². A block of eight TASC will generate approximately 0.749 W. This is about a 20% decrease in power from a single ITJ solar cell. Initial calculations with Satellite Tool Kit (STK) indicate that SCAT will produce up to a maximum power of up to 1.48 W. This power figure is based on the assumed orbital parameters given earlier and a SCAT rotation rate of 0.03 rev/min while illuminated. This rotation rate has been seen on other CubeSats on orbit that contained no attitude stabilizing systems. Solar Panel design is discussed in Appendix A.

¹³ Ortiona et al., "The Naval Postgraduate School SCAT++ CubeSat Program." 7, 2009.

Discussion on power generation estimates and the use of STK for power estimations is contained in Chapter IV.

B. SCAT CONCEPT OF OPERATIONS

1. Overview

To acquire the necessary telemetry, the project team developed a concept of operations. The team divided states of operation into initial modes: Start-Up Operations and Normal Operations. Normal Operations was then subdivided into four additional modes: Transmission Mode, Sun Mode, Eclipse Mode, and Beacon Mode.¹⁴

2. Start-Up Operations

The team defined Start-Up Operations as the time at which NPS-SCAT is deployed. At the time of activation, the FM430 Flight Module is powered on and the satellite starts a four hour timer to allow the EPS battery to begin charging as the actual charge state of the battery will not be know. Normal Operations may be initiated as soon as the battery voltage exceeds a pre-set threshold to be determined later after SCAT testing. If the battery voltage does not increase to preset voltage, the unit will transition to normal operations in an attempt to conduct normal operation in case of an unknown internal failure.¹⁵

¹⁴ M.P. Schroer, *NPS-SCAT; A Cubesat Communicationsv System Design, Test, and Intergration*. Monterey: Naval Postgraduate School thesis, 2009.

¹⁵ M. P. Schroer, *NPS-SCAT; A Cubesat Communicationsv System Design, Test, and Intergration*. Monterey: Naval Postgraduate School thesis, 2009.

3. Normal Operations

Normal Operations include SMS operation, transmission of abbreviated telemetry via the beacon, transmission of primary telemetry via the 2400 radio, and eclipse operations. From Start-Up Operations, Normal Operations will first query the primary radio to see if the satellite is receiving a transmission from an authorized ground station. If receiving, the satellite will proceed to Transmission Mode. If not receiving, then the system will determine if the satellite is in the sun or eclipse. If there is no voltage or very little voltage from the solar panels, then the spacecraft is in eclipse and the software scheduler will transition the system to eclipse mode. If there is voltage from the solar cells, then the software will check to see if the SCAT SMS +Z Axis (Figure 1) is producing voltage, if not, the scheduler will assume control. If the SCAT Z Axis is producing voltage, then a determination of what face is illuminated by measurement of the face temperature, the hotter face being in the sun. Once the software is able to determine SCAT's orbital state based on power generation, battery voltages and the external temperatures, SCAT will transition to the appropriate mode.¹⁶

4. Transmission Mode

Transmission Mode allows the satellite to transmit full telemetry to the ground station. An initial low power receive mode will allow the ground station to contact SCAT

¹⁶ M.P. Schroer, *NPS-SCAT; A Cubesat Communications System Design, Test, and Intergration*. Monterey: Naval Postgraduate School thesis, 2009.

and set an internal system clock. The system clock will allow SCAT to estimate time periods in view of the NPS ground station to allow primary transmission. Because the transmission of full telemetry is power intensive, battery voltage is checked prior to transmission. If the voltage is within pre-defined voltage range of 7.2 V to 8.2 V, the system will prepare to transmit full telemetry when access to the ground station is available.¹⁷

a. Sun Mode

Sun Mode controls the SMS and allows solar cell data recording. If the battery voltage is high enough, and SCAT is in the sun, the SMS will acquire full telemetry. Once complete, if SCAT is still within the illuminated portion of its orbit then three timers will be initiated; one for the Beacon Mode, one to acquire full telemetry, and the third to acquire abbreviated telemetry. The duration requirements of the Beacon timer will be discussed later. The duration of the full telemetry timer is based on taking three solar cell data samples during illumination.¹⁸

b. Eclipse Mode

The purpose of Eclipse Mode is to manage the power draw and to ensure that the beacon only transmits when

¹⁷ M.P. Schroer, *NPS-SCAT; A Cubesat Communicationsv System Design, Test, and Intergration*. Monterey: Naval Postgraduate School thesis, 2009.

¹⁸ M.P. Schroer, *NPS-SCAT; A Cubesat Communicationsv System Design, Test, and Intergration*. Monterey: Naval Postgraduate School thesis, 2009.

sufficient power available from the battery. If there is sufficient voltage, the beacon will transmit on a pre-programmed schedule.¹⁹

c. Beacon Mode

The Beacon Mode allows the transmission of abbreviated telemetry at a fixed interval. This ensures ground reception of solar cell performance data in case the primary radio is unable to transmit the full telemetry data.²⁰

¹⁹ M. P. Schroer, *NPS-SCAT; A Cubesat Communicationsv System Design, Test, and Intergration*. Monterey: Naval Postgraduate School thesis, 2009.

²⁰ M. P. Schroer, *NPS-SCAT; A Cubesat Communicationsv System Design, Test, and Intergration*. Monterey: Naval Postgraduate School thesis, 2009.

III. SATELLITE POWER SYSTEM CONSTRUCTION AND INTEGRATION METHODOLOGY

A. SYSTEMS POWER BUDGET ANALYSIS

The power system budget is made up of the individual power consuming components of SCAT. It was discovered during the analysis of Microhard radio that the manufacturer's claim for power consumption was inaccurate. In the case of the Microhard 2420 radios, the actual power consumed was significantly larger than the manufacturer's claim. The best method of verifying power consumption claims is a direct measurement of component power consumption while operating. For initial satellite power determination, it was not possible to fully integrate the SCAT satellite as control software was not available to allow full integration. The ideal method of determining the complete system power draw is to completely assemble the CubeSat and then directly measure battery current and voltage while in operations; however, this is not always possible and the use of manufacturer data and direct testing of components on hand to conduct initial power budget analysis was used. In the case of SCAT, the following five subsystems were taken into account for power budget considerations FM430, Clyde Space EPS, SMS system, Microhard radio, and Beacon.

Table 3 indicates the power values used in the initial power budget calculations based on both measured and manufacturers data. During testing of the EPS, it was discovered that the EPS 5 V and 3.3 V regulated buses efficiencies vary based on bus load and that the EPS uses

approximately 0.37 W due to parasitic loads of the regulators and battery charge regulator circuitry. As a result of the EPS efficiencies at low power levels, it was found that very small loads placed on the buses by the systems did not show an increase in battery load and were not used in the power budget calculations as the 0.37 W consumed by the EPS took then into account in the power budget calculations. Tables 4 and 5 show results of EPS testing. The efficiency varies from 61% to 80% based on bus load. These efficiencies were taken into account in the MATLAB code that was used achieve the results in Figures 5 and 6. The loads in Table 3 were increased by the bus efficiency of the bus used. For example the MHX Radio uses the 5 V bus and was increase from 4 W to 5 W ($5.19 \text{ W} = 4 \text{ W} / 0.80$) for the power loading simulations.

Subsystem	Mode			
	Off	Stby (mW)	On/Rx(mW)	Transmit(W)
FM430	N/A	10	10	0.010
SMS	N/A	67	294	N/A
MHX Radio	0W	10	1250	4
Beacon	0W	10	1000	1
EPS	N/A	360	360	.36

Table 3. SCAT Component Power Consumption

Resistance Ω measured/actual	Battery (V) with load on 5Vdc reg	Battery (A) with load on 5Vdc reg	5Vdc reg. voltage	5Vdc reg. current	EPS Efficiency 5V bus
10.0 / 10.7	7.19	0.407	4.98	0.465	79.13
8.1 / 8.9	7.15	0.489	4.98	0.562	80.05
5.8 / 6.6	7.06	0.657	4.97	0.746	79.93
4.3 / 4.8	6.9	0.954	4.96	1.03	77.61
4.0 / 4.3	7	tripped	2.5	trip < 1.16	NA
3.5 / 4.4	NA	NA	NA	NA	NA
3.3 / 4.0	NA	NA	NA	NA	NA
3.0 / 3.7	NA	NA	NA	NA	NA
2.7 / 3.5	NA	NA	NA	NA	NA

At 6.93 Vdc The battery voltage was to low to provide sufficent voltage to the regulators.

Table 4. EPS 5 V Bus Efficiency Testing

Resistance Ω measured/actual	Battery (V) with load on 3.3Vdc reg.	Battery (A) with load on 3.3Vdc reg.	3.3Vdc reg. voltage	3.3Vdc reg. current	EPS Efficiency 3.3V bus
10.0 / 10.7	7.27	0.196	3.28	0.306	70.44
8.1 / 8.9	7.24	0.269	3.25	0.366	61.08
5.8 / 6.6	7.2	0.294	3.27	0.49	75.69
4.3 / 4.8	7.11	0.403	3.26	0.679	77.25
4.0 / 4.3	6.97	0.454	3.26	0.751	77.37
3.5 / 4.4	6.96	0.442	3.26	0.73	77.36
3.3 / 4.0	6.875	0.541	3.12	0.773	64.84
3.0 / 3.7	6.77	0.54	3.25	0.863	76.72
2.7 / 3.5	6.65	0.645	3.18	0.9	66.72

Table 5. EPS 3.3 V Bus Efficiency Testing

B. POWER AVAILABLE ANALYSIS

Available power analysis was completed using an STK solar analysis tool to simulate solar power generated over SCAT's orbit. Figure 4 is a screen capture of the STK solar tool screen. An STK model of SCAT was created including the location and orientation of the solar panels on SCAT's surfaces. STK was also used to determine the communications access periods in which SCAT would be able to communicate with the NPS ground station and transmit via the primary

Microhard radio. The sunlit periods were also calculated for determination of SMS operations. The combination of data calculated by STK was used in a MATLAB program to perform the actual power budget calculations. Table 6 shows a total time of 5066 simulated minutes which correlates to 56 SCAT orbits. As the STK simulation generates the estimated power in Watts for every minute of simulation, the units of Watt minute or Watt hours will be used for the energy budget discussion. The generated energy results are listed in Table 7. As the simulation lasting 5066 minutes, SCAT will generate about 3260 Wmin (54.40 Whrs) over the total simulation time. This averages to 0.966 Whrs each SCAT orbit and an overall average power generation of 0.644 W over an entire orbit.

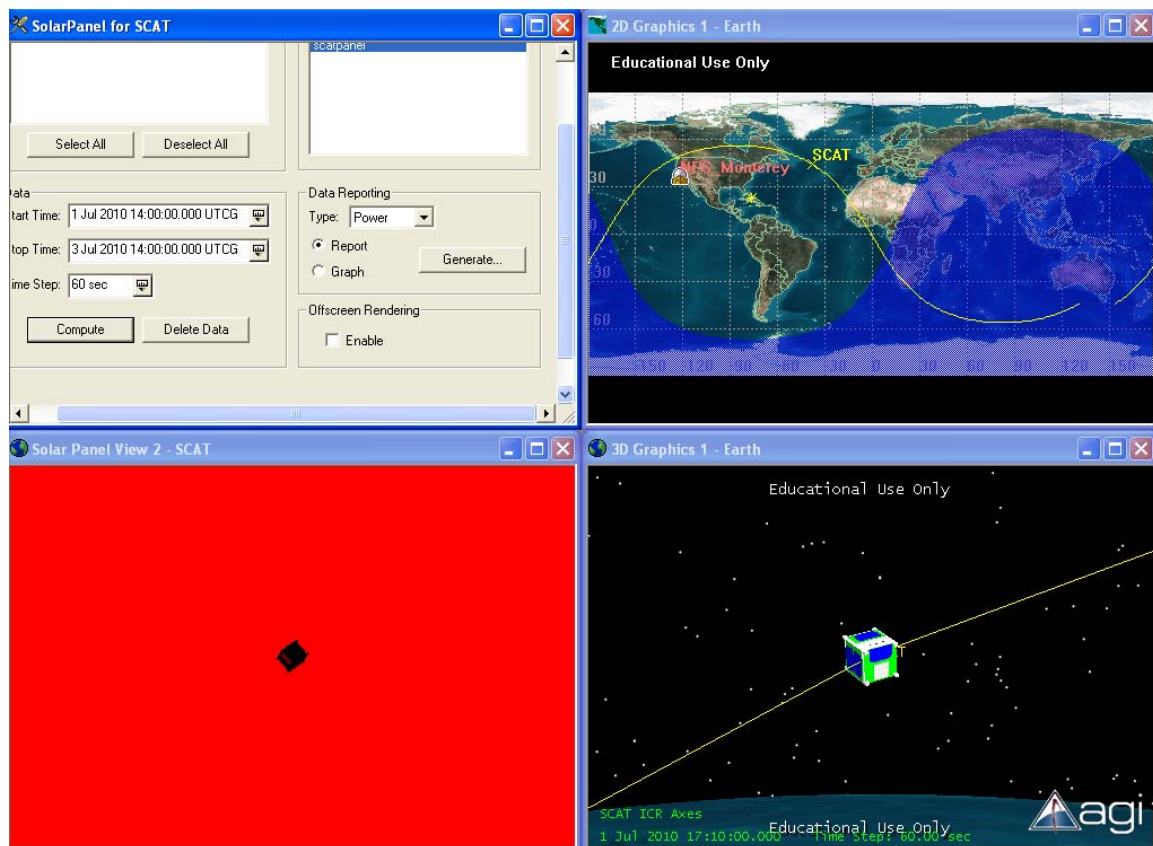


Figure 4. STK Solar Power Analysis Tool on SCAT
22

C. OPERATIONAL POWER SCENARIOS

The initial operations plan for SCAT had the unit conducting a four-hour battery charge period after deployment. The unit would then begin beacon transmissions on a ~20% duty cycle transmitting abbreviated telemetry data. It would also conduct Microhard primary data transmission when over the NPS ground station. As shown in Table 6, the power loads of the subsystems using the Watt hour method discussed in section B above, it can be seen that 0.966 Whrs per orbit will be used. Comparing the energy used with the energy generated (0.966 Whrs per orbit) it is clear that there is almost zero margin (0.24%) to recharge SCAT batteries. SCAT subsystem power and margin data are shown in Tables 6 and 7. The small power margin would result in the eventual discharge of the batteries until continuous shut downs of SCAT would occur from the EPS battery protection feature at 6.4 V. SCAT normal operations would reactivate upon the battery reaching 7.5 V. As the priority of SCAT operations is taking SMS readings and transmitting the full telemetry data back to the NPS ground station, the only subsystem open to manipulation with respect to power saving is the beacon secondary transmissions. Lowering the beacon duty cycle to 14.4%, produces a power margin of 10%. This will allow the safe charging of the SCAT battery, without fear of fail-safe shut downs and possible loss of data or the unit itself.

SMS Power (0.367W)		Beacon (1.25W)		MHX(5.0W)		Basic EPS (0.36W)		Total Load Power Used	
156	activations mins per sim	988	BCN mins	23	Tx mins per Sim	1849.09	Watt*mins per sim		
3	activations per orbit	18	BCN per orbit	0.20	Tx mins per orbit				
0.954	W*Hr per Sim	20.583	W*Hr per Sim	1.917	W*hr per sim	30.818	W*Hr per Sim	54.272	W*hr per sim
0.017	W*hrs/orbit	0.366	W*hrs per orbit	0.034	W*hrs per orbit	0.548	W*hrs per orbit	0.964	W*Hrs/Orbit
		19.50%	BCN Duty Cycle						

Table 6. SCAT loads, per total simulation time and load per orbit. ~20% Beacon duty cycle

SMS Power (0.367W)		Beacon (1.25W)		MHX(5.0W)		Basic EPS (0.36W)		Total Load Power Used	
156	activations mins per sim	730	BCN mins	23	Tx mins per Sim	1849.09	Watt*mins per sim		
3	activations per orbit	13	BCN per orbit	0.20	Tx mins per orbit				
0.954	W*Hr per Sim	15.208	W*Hr per Sim	1.917	W*hr per sim	30.818	W*Hr per Sim	48.897	W*hr per sim
0.017	W*hrs/orbit	0.270	W*hrs per orbit	0.034	W*hrs per orbit	0.548	W*hrs per orbit	0.869	W*Hrs/Orbit
		14.41%	BCN Duty Cycle						

Table 7. SCAT loads, per total simulation time and load per orbit. ~14.4% Beacon duty cycle

MATLAB was used to produce simulated power profiles for SCAT just after launch, using the 14.4% beacon duty cycle. The MATLAB code and sample input files are located in Appendix E. Figures 5 and 6 are simulated power profiles for the initial launch and power generation of SCAT. The simulation assumes SCAT begins at half of full power capacity. Simulations show SCAT will become fully charged within the first 4000 minutes (67 hours) of activation. The loads include the 1 W beacon with a 14.4% duty cycle throughout the orbit. The large load peaks represent the periods in the orbit with a communications window, transmitting to the ground station located at NPS in Monterey, California. The simulation shows in Figure 6 that with the power generation and the expected loads, the SCAT battery should not drop below 95% of full charge once the initial charge is complete.

Discharge and charge testing of the EPS Lithium Polymer (Lipo) battery show the battery is operating within design specifications. Figures 7 and 8 show the discharge and charge curves of the Clyde Space Lipo battery. The EPS has a built in battery fail safe and will secure EPS loads if the battery voltage drops below 6.4 V (or 3.2 V for an individual cell) and will reinitialize loads when the battery has recharged to 7.5 V. The EPS battery is designed with an integrated battery heater that keeps the battery within operating parameters. This is important as the capacity of the Lipo battery decreases with temperature. Figure 9²¹ shows an example of a similar Lipo battery response to varying temperatures. It can be seen that the capacity can drop as much as 15% of the rated capacity. According to the Clyde Space Lipo battery documentation, the cells in use have been tested from -15° C to +40° C and have a capacity of 1300 mAh over 1500 cycles with a 30% depth of discharge. This should be more than sufficient as simulations indicate a continuous discharge cycling of only 5% when the battery reaches its fully charged state. The initial recommendation is that the SCAT program should be set to secure loads when battery voltage reaches 7.0 V and restore operations at 7.5 V. This would be high enough to prevent an EPS failsafe operation and also high enough to support all loads as required.

²¹ Varta Super polymer Technology technical Handbook, February 2007, www.varta-microbattery.com.

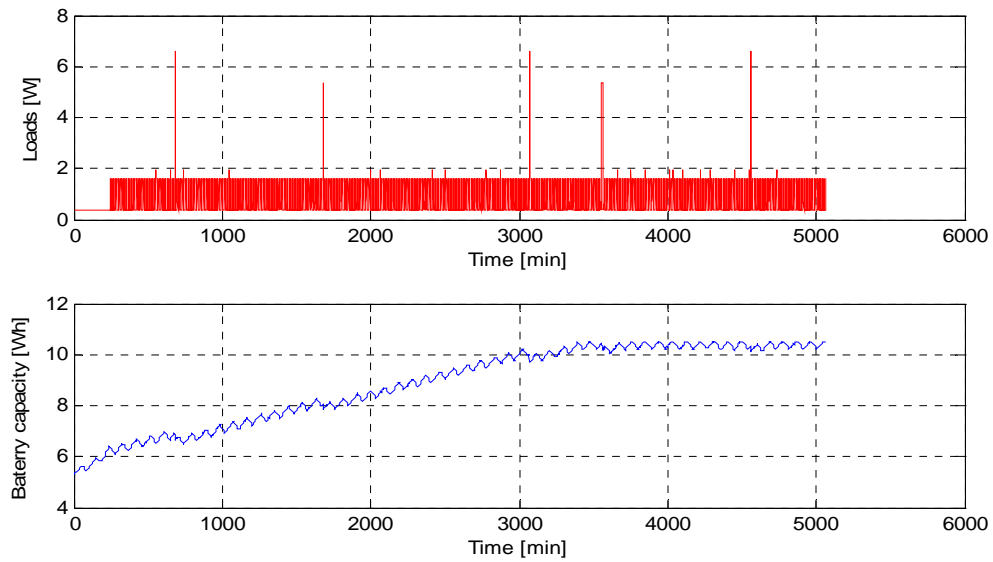


Figure 5. Battery Capacity and loads after launch assuming the battery at 50% of capacity with 4 hour wait

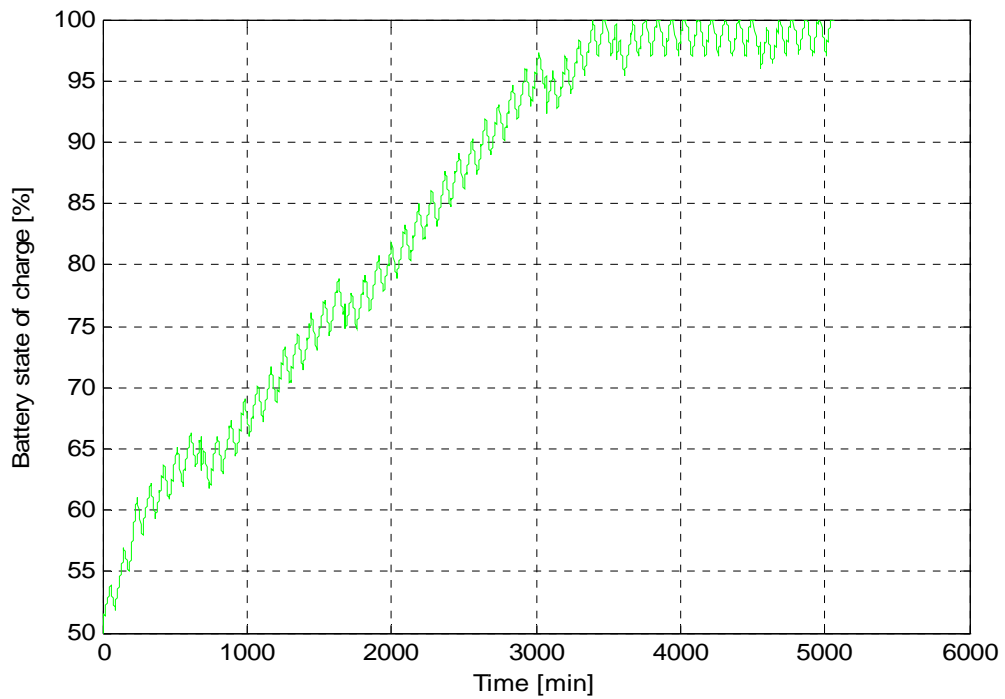


Figure 6. SCAT battery capacity vs time after launch at 50% battery capacity with 4 hour wait

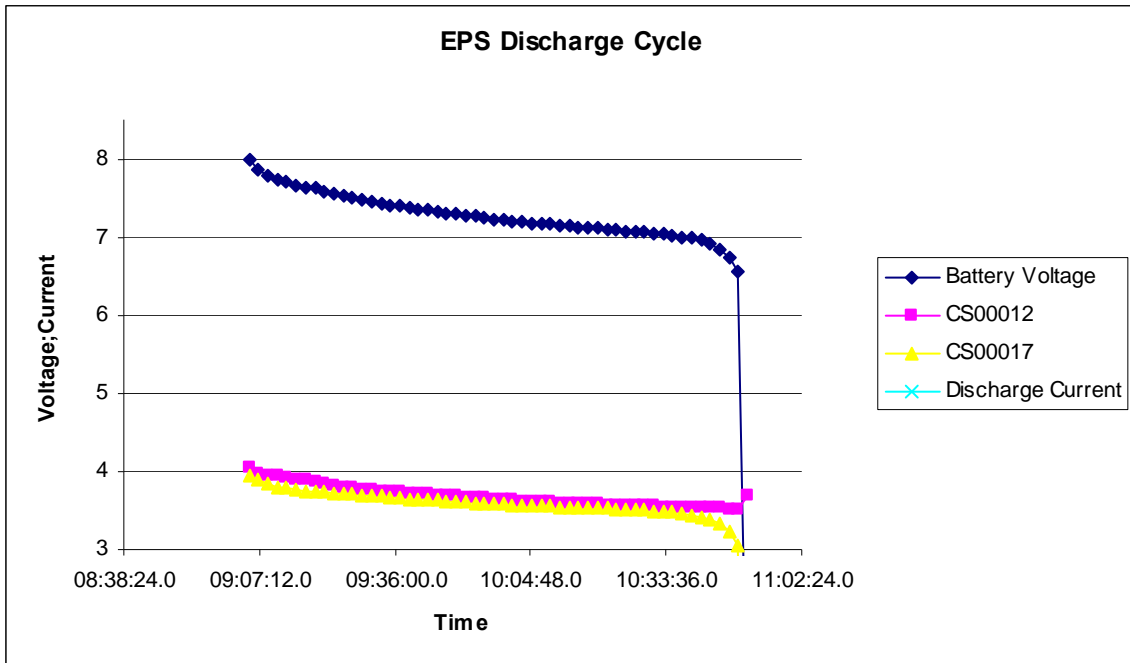


Figure 7. Clyde Space EPS Battery Discharge test with 12.6 Ohm load. Note: Cell CS00017 weaker of the two cells

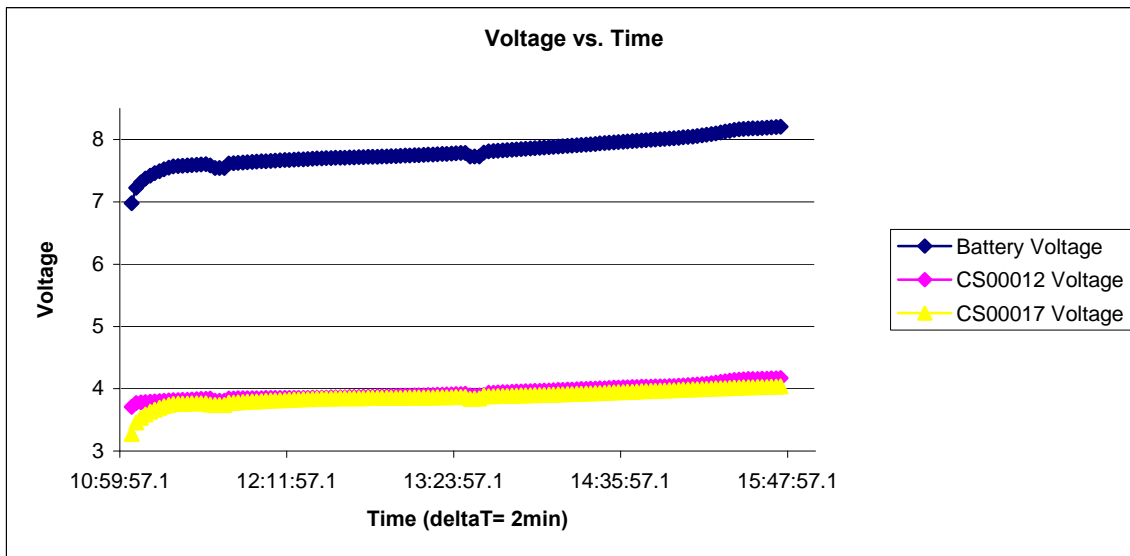


Figure 8. Clyde Space EPS Battery Charge test

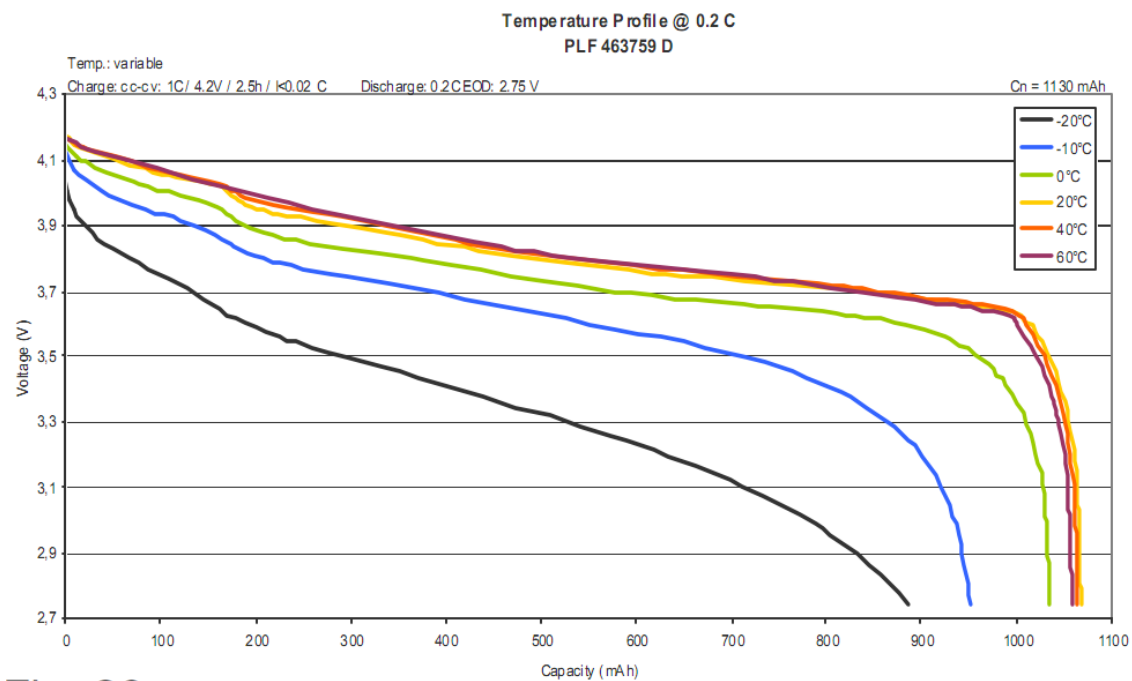


Figure 9. Example battery Capacity VS Temperature

IV. SIMULATION FOR CUBESAT OPERATION ON ORBIT

A. STK SIMULATION

The SCAT STK simulation used the following information to provide data for the use in power budget calculations. Inputs into STK are as follows: orbit altitude 410 km, Inclination 51.6 degrees, Ground Station is Naval Postgraduate School, Monterey, California. Communications range constraints 850 km and 10 degrees elevation. The results were an orbit time of 92.77 minutes with a maximum eclipse time of 36 minutes and a sun time of 56 minutes.

STK was used to provide simulated power generation per minute of orbit and also the access time that SCAT will have with NPS. The outputs for power and access times were integrated into the MATLAB power simulation discussed section B.

B. MATLAB SIMULATION

The MATLAB code used for the power simulation was modified from a previous NPS student's thesis work.²² The MATLAB file Power_Budget.m located in Appendix F allows for the creation of the power profile simulation. Using the data created from the STK simulation, power, solar intensity, and link status, along with SCAT loads and initial battery state, the program will predict the battery charge state over time. The following initial conditions were assumed for the power calculations: the SMS will take four I-V curves

²²F. Rossberg, "Simulation of the deployment and orbit operations of the NPS SCAT CubeSat," Naval Postgraduate thesis, 2008.

whenever SCAT is illuminated by the sun each orbit. The beacon will have a 14.4% duty cycle as simulated by a one in seven minute on time. The MHX 2400 radio will only transmit when the SCAT has access to the NPS downlink station. By analyzing the power profile one can determine if the solar power is sufficient to support SCAT power loads. In Figures 5 and 6, starting with an initial battery state of 50%, one can see the system has the capability to recharge and support system loads.

V. CONCLUSIONS AND FUTURE WORK

The Clyde Space power system selected will support SCAT's operational requirements. Additionally, significant experience was gained during the design and manufacture of the SCAT solar panels. If using a COTS EPS, documentation should be thoroughly analyzed before final selection. Ideally, documentation should include schematic layouts and complete EPS limitations and characteristics. Thorough review of EPS feedback from actual users should be read and understood prior to EPS selection. It was learned that system loads should also be thoroughly analyzed before EPS selection to ensure adequate EPS selection.

For SCAT to achieve an adequate power margin to ensure adequate power and battery charging throughout the operational period of SCAT, the beacon duty cycle needs to be changed from 20% to 14.4% to achieve a 10% power margin. Also, the effectiveness of the EPS battery heaters needs to be evaluated to ensure that the battery remains within temperature specifications. When available, the beacon's power usage should be fully characterized. Finally, once the integration of all of the SCAT subsystems has been completed, a real time power characterization should be done to verify power budget calculations and estimations. Once complete, the beacon duty cycle should be modified to support a 10% power margin.

Future work for the SCAT project includes completion of required testing of the prototype unit to verify satisfactory integration and operation. Remaining SCAT testing includes temperature and vacuum testing to ensure

SCAT survival in the space environment, and shake testing must be completed to ensure launch survivability. Once proof of design testing has been completed and weaknesses have been identified and corrected, the final launch unit will be built, tested, and readied for the next available launch window. Other items to be completed include the build and testing of the NPS ground station in preparation for SCAT downlink operations.

APPENDIX A. SOLAR PANEL DESIGN

The goal of any solar panel design is to maximize power generation to support system loads. In the case of a CubeSat, surface area is at a premium so careful design is a requirement. A CubeSat has a maximum total area of 600 cm^2 of area to work with (six 10cm by 10cm sides). In the case of SCAT, one face will be largely dedicated to the SMS and testing of experimental solar cells and may be unusable for power generation. Another side will contain the Microhard radio patch antennae, but will have room to allow placement of some power generating solar cells. Another side has the programming and charging connections, which also limits power generation solar cell placement. This leaves three sides for dedicated solar cell placement. MAX6632 temperature sensors were also mounted on both sides of each solar panel, to determine panel temperature and thereby, whether the panel is currently illuminated or not.

The cells selected for power generation are Spectrolab Improved Triple Junction Cells rated at 26.8% efficiency. A better choice of cells would be the Spectrolab Ultra Triple Junction cells at 28.3% efficiency; however, they were not available in the quantity required for this project so the ITJ cells were purchased.

For the circuit board designs, each SCAT outer board surface template was designed via a CAD program. Those CAD templates were imported from CAD into PCB Artist software. PCB Artist is a free schematic and PCB design program provided by Advanced Circuits, a PCB manufacturer. The

company website is www.4pcb.com. The boards they produce are good for prototyping and final production of PCB design requirements.

The design process begins with creation of an electrical schematic of each solar panel in the software. The next step is conversion of the schematic to a PCB layout using the actual physical components to be used. The connectors and solar panels had to be created as the software did not contain the components. During the physical layout of the PCB the following design guidelines were used: the number and size of electrical traces located on the top and bottom PCB surfaces should be minimized to prevent electrical shorts and inadvertent reception of electrical signals. Minimize or eliminate the use of 90 degree bends in PCB traces. This also minimized RF interference due to the changes in impedance of the PCB trace as it bends 90 degrees. This concern is mostly directed at signals in the megahertz range and greater; however, as SCAT will be exposed to high-frequency radiation, it is prudent to use good engineering practices and minimize 90-degree traces where possible.²³ Circuit trace vias should not be placed under any areas where solar cells will be mounted. This prevents the formation of air pockets and possible cell damage when using NuSil double-sided tape to mount the cells to the PCB.²⁴ Air bubbles will expand in a vacuum and possibly crack the cell. One PCB electrical layer should be a ground plane to allow for even distribution of temperature

²³ R. Hood and K. Armstrong, "PCB Design and Electromagnetic Radiation" http://www.ami.ac.uk/courses/topics/0006_emcpcb/index.html.

²⁴ D. Hinkley, Aerospace Corporation; Personal communication and demonstrations of NuSil tape installation, 19 March 2009.

across the board and also minimized electrical interference. The second layer of the six layer board was designated the ground plane. This allows for even distribution of panel heating.

The process of designing the PCB panels is an iterative process. One should never solely rely on one person for critical designs such as SCAT. For space based systems, once deployed there is no way to repair or replace poor designs as with earth based systems, correct design is critical. As each board was designed, each revision of board was reviewed by both student peers and instructors. Numerous design error and improvements were discovered during each revision until the final design was achieved. As confident as a designer may be in their design, there are usually improvements that a second set of eyes can make.

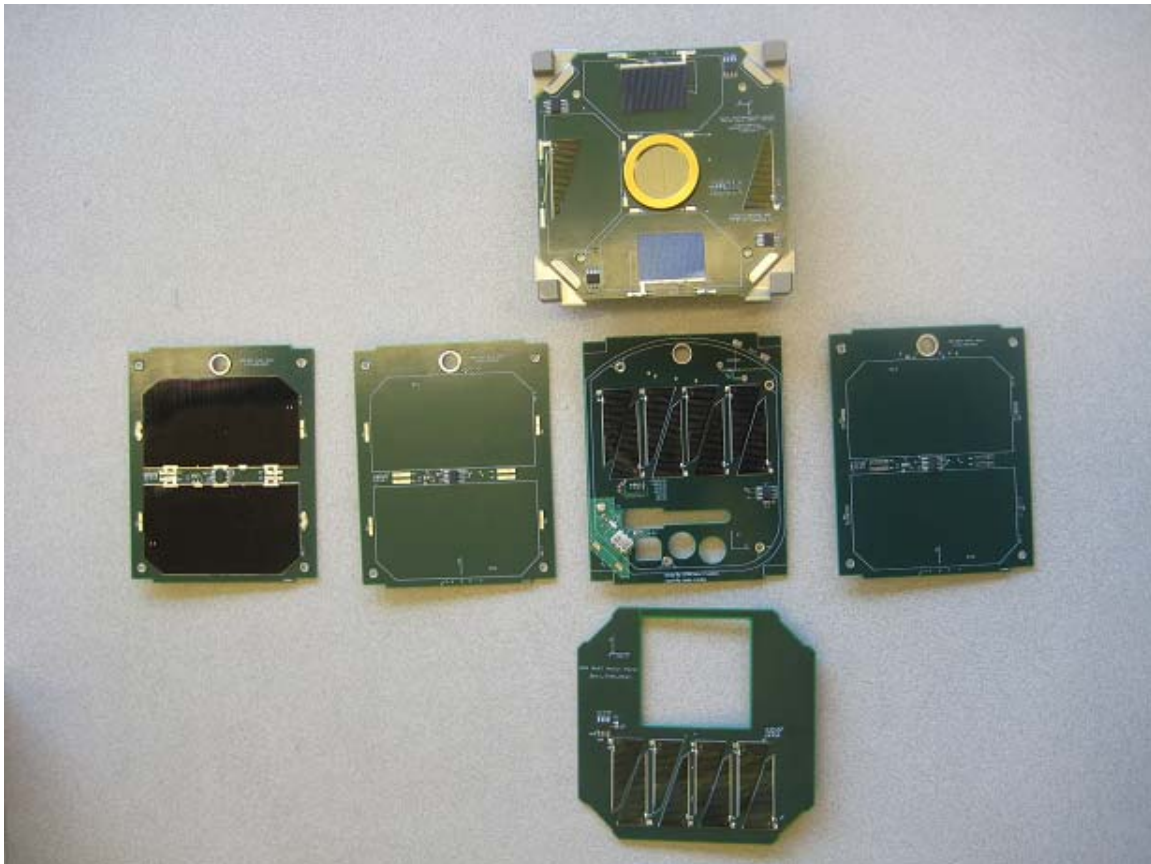


Figure 10. Final power panel designs. Top: +Z axis SMS PCB board still undergoing modifications. Middle (L-R): -Y, +X, +Y, -X axis power PCB boards. Bottom: -Z axis power and Patch antenna PCB board.

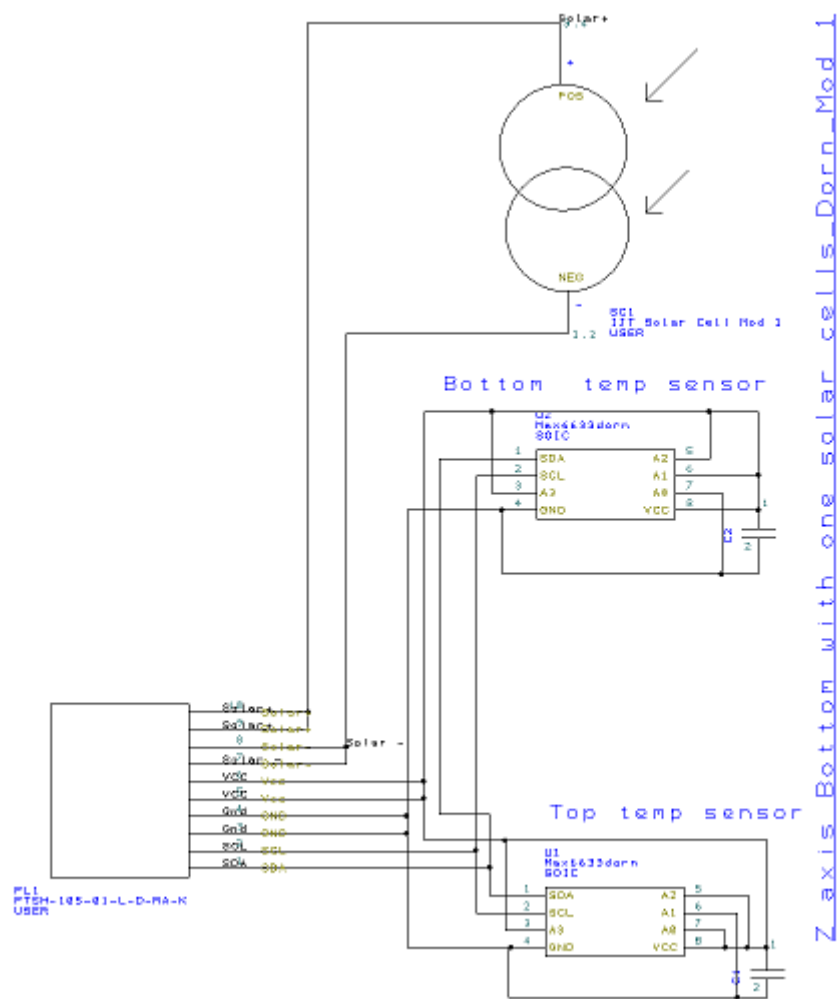


Figure 11. -Z axis schematic

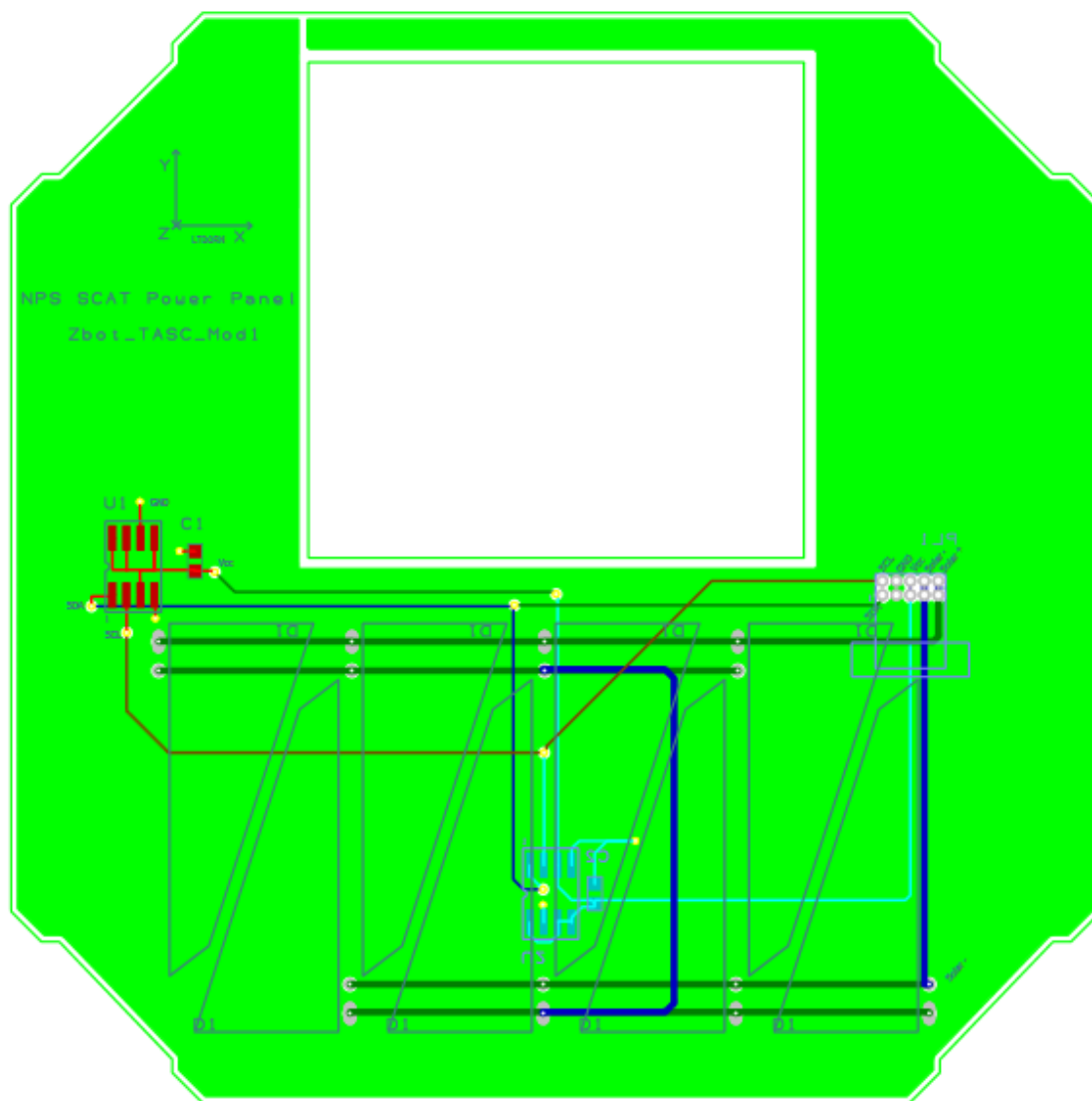


Figure 12. -Z Axis Bottom component layout

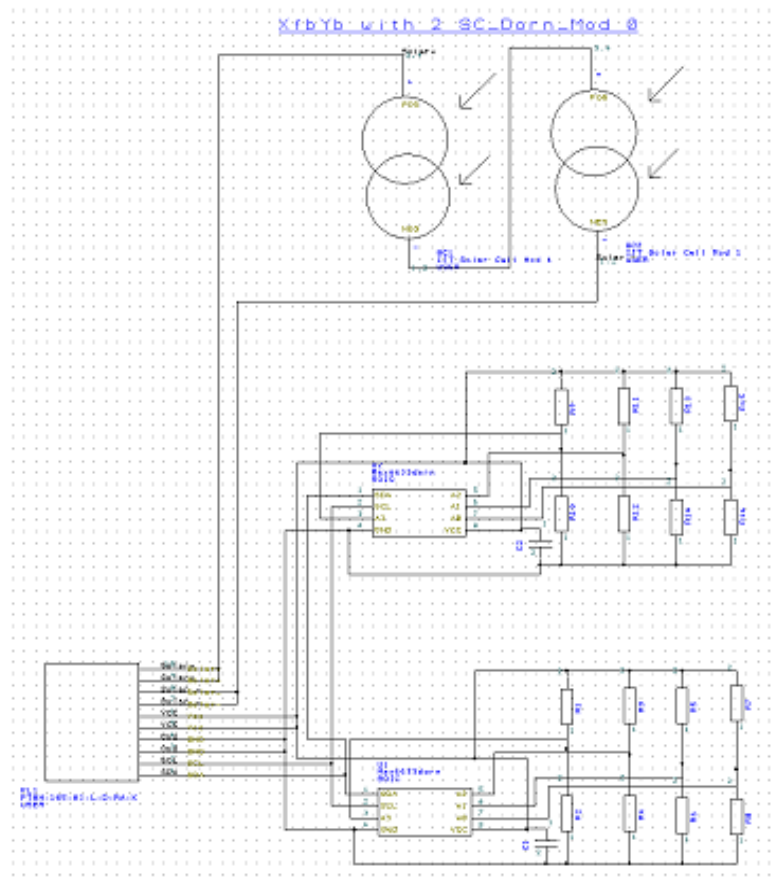


Figure 13. -Y, +X, -X power board two cell schematic

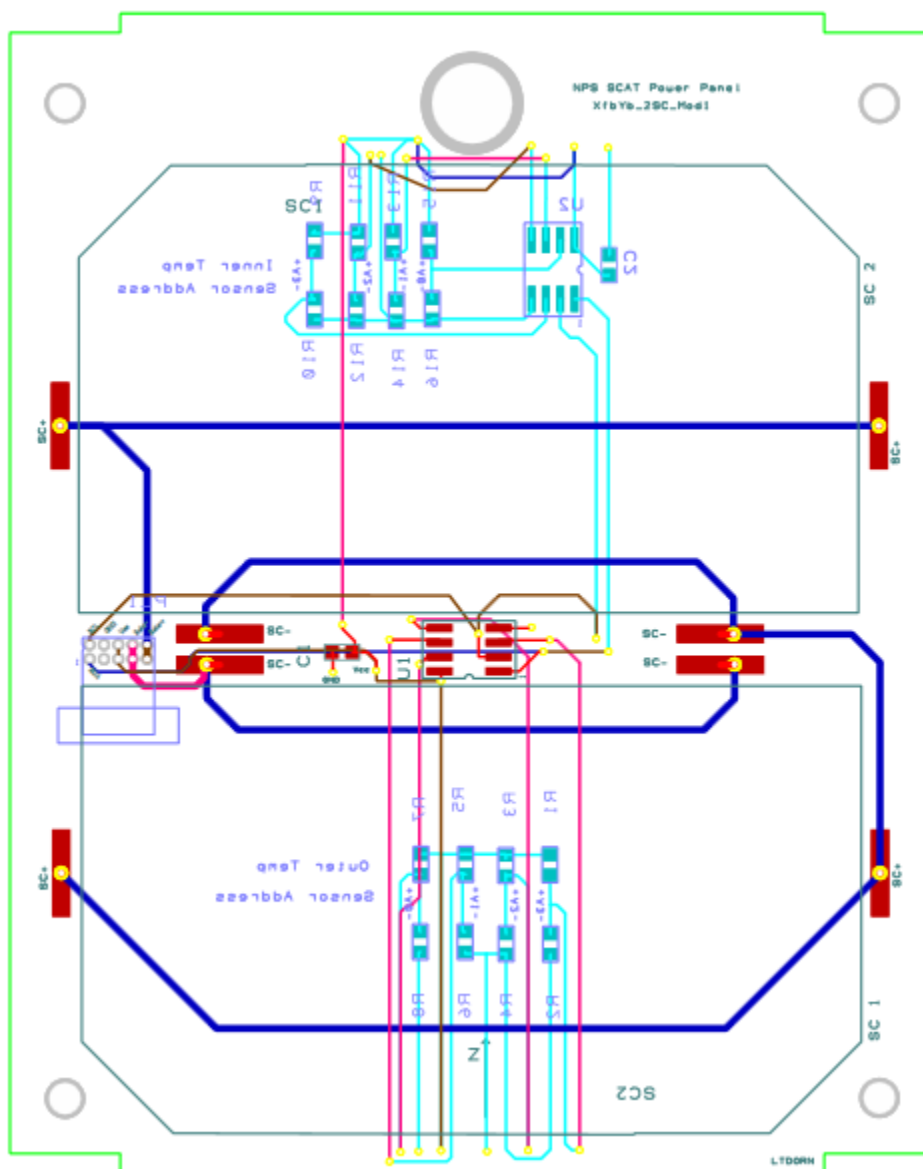


Figure 14. -Y, +X, -X power board two cell two cell component layout

APPENDIX B. SCAT STK MODEL

The following STK model was used for the solar simulation of the SCAT CubeSat. The original design consisted of all ITJ CIC solar cells and power calculations were based on the model in Figure 15. However, the final design consists of two banks of four TASC cells in series on each panel that has one CIC cell.

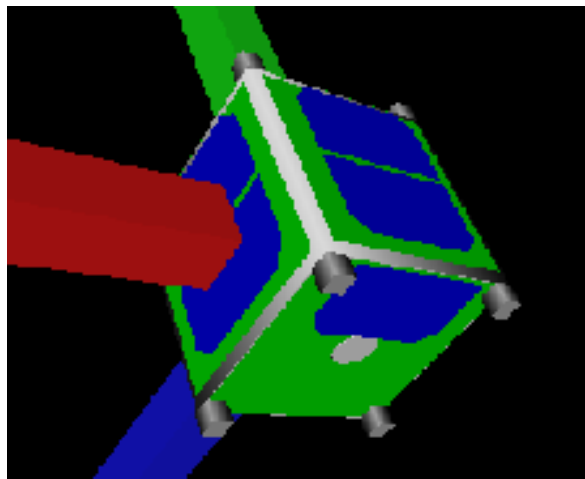


Figure 15. SCAT STK model

```
#####  
#=====#  
#          THE NPS-SCAT CUBESAT DORN          #  
#=====#  
# Setting cell efficiency  
SolarPanelGroup scatpanel 26.0  
#26.0 is the cell efficiency  
#SolarCells Power, this creates the actual outline of  
#the Spectrolabs cell given in six points going around  
#in a CCW direction. It names the cells SolCells and  
#sets this as the component that will create the solar  
#power (scatpanel). The cells are colored blue. The  
#term SolarPanelGroup is used by STK to identify the
```

#components that will be used to estimate solar power
#generated based on the components surface area in
#relation to the incoming sun angle to the component.
#All point units below are in meters. Each data point
#is given in an X,Y,Z reference.

Component SolCells

SolarPanel scatpanel

Polygon

FaceColor blue

Shininess 64

Specularity 0.4

Numverts 6

Data

0 0 0

0 0.069 0

0 0.069 .031

0 0.0608 0.0395

0 0.0081 0.0395

0 0 0.031

EndPolygon

EndComponent

Main structure

Component Body

Rotate 45 0 0

Translate 0 0.05 0.05

Cylinder

FaceColor silver

NumSides 4

Face1Radius 0.07

Face1Normal -1 0 0

Face2Radius 0.07

Face2Normal 1 0 0

Length 0.1

```

        EndCylinder
    EndComponent

#####    SunSensor. Creates a cylinder with a radius of
#0.01m and 0.0005m long.
Component SunSensor
    Cylinder
        FaceColor white
        NumSides 25
        Face1Radius 0.010
        Face1Normal 1 0 0
        Face2Radius 0.010
        Face2Normal 1 0 0
        Length 0.0005
    EndCylinder
EndComponent

#####    Patch Ant. Creates the patch ant component. A
#square of 4 points and sets color.
Component Patchant
    Polygon
        FaceColor grey
        NumVerts 4
        Data
            0 0 0
            0 0.045 0
            0 0.045 0.045
            0 0 0.045
    EndPolygon
EndComponent

#####    Connectors. Creating the connectors for the USB
#and power connections of the stock cubesat kit.
Component Connector
    Cylinder
        FaceColor gray20

```

```

        NumSides 16
        Face1Radius 0.003
        Face1Normal 1 0 0
        Face2Radius 0.003
        Face2Normal -1 0 0
        Length 0.0005
    EndCylinder
EndComponent
##### Panels for SolarCells mounting. This creates
#the six panels on the sides of the CubeSat.
Component Panel
    Polygon
        FaceColor green
        NumVerts 4
        Data
            0 0 0
            0 0.09 0
            0 0.09 0.09
            0 0 0.09
    EndPolygon
EndComponent
Component Panel2
    Polygon
        FaceColor green
        NumVerts 4
        Data
            0 0 0.045
            0 0.09 0.045
            0 0.09 0.095
            0 0 0.095
    EndPolygon
EndComponent

```

```

Component Panel3
    Polygon
        FaceColor green
        NumVerts 4
        Data
            0 0 0
            0 0.098 00
            0 0.098 0.098
            0 0 0.098
        EndPolygon
    EndComponent

##### Assembly SolarCell sidepanel. This panel is
#a panel with two solar cells on it rotated and shifted
#as required.

Component SidePanel
    Refer
        Component Panel
    EndRefer

# adds the one solar cell rotated and shifted as
#required.

    Refer
        Rotate 0 180 0
        Translate 0.002 0.009 0.042
        Component SolCells
    EndRefer

#adds the second solar cell rotated and shifted as
#required.

    Refer
        Translate 0.002 0.009 0.045
        Component SolCells
    EndRefer
EndComponent

##### Top panel. Creates the top panel with the sun
#sensor and one solar cell placed on it as required.

```

```

Component Top
    Refer
    Translate 0.0001 0.001 0.001
    Component Panel3
    EndRefer
    Refer
    Translate 0 0.05 0.05
    Component SunSensor
    EndRefer
    Refer
    Translate 0.001 0.015 0.002
    Component SolCells
    EndRefer
EndComponent
#####    Bottom panel
Component BottomPanel
    Refer
    Translate 0.0001 0.001 0.001
    Component Panel3
    EndRefer
#Below adds the patch ant created earlier to the
#bottom panel and is offset from the center of the
#panel.
    Refer
    Translate 0.001 0.025 0.05
    Component Patchant
    EndRefer
#Below adds the solar cell CIC created earlier to the
#bottom panel and is offset from the center of the
#panel.
    Refer
    Translate 0.001 0.015 0.002
    Component SolCells

```

```

        EndRefer
EndComponent
#####   AntennaPanel
Component AntennaPanel
    Refer
    Translate 0.0005 0 0
    Component Panel2
    EndRefer
    Refer
    Translate -0.001 0.009 0.05
    Component SolCells
    EndRefer
    Refer
    Translate -0.0005 0.025 0.015
    Component Connector
    EndRefer
    Refer
    Translate 0-0.0005 0.045 0.015
    Component Connector
    EndRefer
    Refer
    Translate -0.0005 0.065 0.015
    Component Connector
    EndRefer
EndComponent
#####   Spacer. These are the CubeSat standoffs on the
#bottom of the cubesat.
Component Spacer
    Rotate 45 0 0
    Cylinder
        FaceColor grey
        NumSides 4

```



```

        Face1Radius 0.007
        Face1Normal -1 0 0
        Face2Radius 0.007
        Face2Normal 1 0 0
        Length 0.01
    EndCylinder
EndComponent
#####
#      NPS-SCAT COMPLETE      #
#####
#This uses all the panels created above and adds them
#to the body created at the beginning of the code.
Component npssc
    Rotate 0 0 90
    Translate 0.05 -0.05 -0.05
    Rotate 180 0 0
    Rotate 0 180 0
    Root
    Refer
    Component body
    EndRefer
    Refer
    Translate 0.001 0 -0.1
    Rotate 0 -180 0
    Component BottomPanel
    Endrefer
    Refer
    Rotate 0 0 90
    Rotate 0 90 0
    Translate 0.005 0.101 0.005
    Component SidePanel
    EndRefer

```

```

Refer
Rotate 0 90 0
Translate 0.005 0.005 -0.001
Component SidePanel
EndRefer
Refer
Rotate 0 -90 0
Rotate 90 0 0
Translate 0.095 -0.001 0.005
Component SidePanel
EndRefer
Refer
Translate 0.1 0 0
Component Top
Endrefer
Refer
Rotate 0 90 0
Translate 0 0.005 0.101
Component AntennaPanel
Endrefer
Refer
Translate -0.01 0.005 0.005
Component Spacer
EndRefer
Refer
Translate -0.01 0.095 0.005
Component Spacer
EndRefer
Refer
Translate -0.01 0.005 0.095
Component Spacer
EndRefer
Refer

```

```
Translate -0.01 0.095 0.095
Component Spacer
EndRefer
Refer
Translate 0.1 0.005 0.005
Component Spacer
EndRefer
Refer
Translate 0.1 0.095 0.005
Component Spacer
EndRefer
Refer
Translate 0.1 0.005 0.095
Component Spacer
EndRefer
Refer
Translate 0.1 0.095 0.095
Component Spacer
EndRefer
EndComponent
```

APPENDIX C. SOLAR CELL APPLICATION WITH NUSIL TAPE

This appendix describes the procedure for installation of solar cells to a PCB solar panel with NuSil double-sided adhesive tape.

A. ACRONYMS

The following is a list of acronyms used in this document:

NPS	Naval Postgraduate School
SCAT	Solar Cell Array Tester
EPS	Electrical Power System

B. PARTS AND EQUIPMENT

1. Parts List

a. Spectrolab IJT Solar Cells: Spectrolab IJT solar cell assemblies that include cover glass and interconnects in a rectangular cropped corner version. The cell assemblies include interconnects, cover glass, and an integral bypass diode.

b. Spectrolab TASC Solar Cells: the TASC solar cells are UJT type. They do not include cover glass, interconnects or integral bypass diode.

c. Solar Cell Boards with electrical components already mounted and tested. Note: Components should be tested prior to installation of solar cells to limit the

possibility of a defective panel after solar cell installation as solar cells will be irremovable after installation.

d. NuSil CV4-1161-5 Adhesive Tape (double-sided)

e. Interconnects: H style connector interconnects will be modified to support the installation of the ITJ solar cells. TASC cells electrical connections are also modified as required. The finished size will be based on the size, shape and location of the mounting pads on the solar cell boards and best engineering practices will be used to determine the best shapes to meet requirements. All electrical interconnects located under a solar cell should not be any thicker than the NuSil double sided tape to prevent cracking of the cell on application pressure.

f. Solar cell outline templates to allow for cutting of solar cell outlines in the NuSil Adhesive Tape. The ones designed for SCAT were made from 1/8 inch aluminum stock.

2. Equipment List

- a. Kapton tape if required
- b. Solder
- c. Soldering iron
- d. Precision Shears (scissors)
- e. Rubber gloves
- f. Safety glasses
- g. Squeegee or soft but firm credit card type material. Must not scratch surface of solar cell glass

- h. Solvent and flux remover
- i. Aero duster (compressed air equivalent)
- J. soft foam piece as large as the solar panel
- k. Laboratory grade isopropyl alcohol
- l. New sharp Exacto knife or equivalent cutting device for cutting NuSil CV4-1161-5 Adhesive Tape.

C. SOLAR CELL APPLICATION

1. Assumptions

The following assumes that all other components required for operation of the solar cell have been soldered to the solar cell power board. Once the solar cells are installed, any attempt to remove the cells will likely result in the destruction of the cells. It is important to ensure the other components are in working order prior to solar cell application as once solar cell application is complete the handling of the boards will need to be minimized to limit the exposure of the cells to damage.

NOTE: The use of a circuit via under the solar cell mounting area should be eliminated or minimized to prevent bubble formations under the cells. An air bubble under the cells can expand and possibly crack the cells during vacuum testing or the vacuum of space. If a via is present under a cell location it is possible to carefully shave the via down to board surface level with a very sharp Exacto knife, being very careful not to gouge the board in the process. This

process was used during the initial prototype construction. All follow-on board designs contained no via under cell mounting areas.

2. Solar Cell Preparation

a. Follow procedures for entering the clean room. Handle cells with rubber glove to prevent finger print oils on cells.

b. While removing the cells from the storage container, inspect for stress marks in the silicon, cracks, and point defects. Set aside cells with defects.

c. Flatten and reform the cell interconnects that might have been bent during shipping.

d. Modify interconnects as required to match board solder points. Interconnects soldered to the bottom of the cell should not be thicker than the NuSil CV4-1161-5 Adhesive Tape. IJT and TASC cells will require the bottom interconnects to be carefully soldered in place prior to application to the board.

e. Solder each interconnect using the minimum quantity of solder possible while still creating a solid bond between the back of the cell and interconnect. The solder joint should not add any significant height to the connection. Use isopropyl alcohol or solvent flux cleaner to clean the flux off of the PCB substrate.

f. Repeat for all required solar cells.

3. NuSil CV4-1161-5 Adhesive Tape Preparation

a. Examine the NuSil tape for any tear or defects.

b. Examine the solar cell metal templates for defects that will prevent clean cuts of the NuSil tape. Replace template if defective.

c. Ensure there is adequate tape to allow the proper cut out of the solar cell template. Place template on NuSil Tape. Ensure placement if cell template allows the maximum efficient use of available NuSil Tape.

d. Using a new sharp Exacto blade, cut around the outline of the template. Remove tape cutout from sheet and inspect. There should be no tears or rips in tape.

e. Repeat as required for all solar cells to be mounted.

4. Solar Board Preparation

a. Examine board for defects. Examine mounted components for defects. Electrical testing of board should have already been complete.

b. Examine area where solar cells are to be mounted. Areas should be clear of defects and the surface should be smooth.

c. Clean surface with Solvent and flux remover as required. Final cleaning of area should be with Laboratory grade isopropyl alcohol and lint free cloth or towel.

5. Mounting Solar Cell to Board

a. Place NuSil Tape over final position of cell on the board. Verify correct positioning and layout.

b. Remove the protective covering on the side of the NuSil Tape that will make contact with the Solar board.

Ensure the exposed tape only contacts the board. Carefully place the tape in the required spot on the board. ENSURE NO AIR BUBBLES GET TRAPPED UNDER THE TAPE. The best method of application would be to allow one tip of the tape to contact the board and then roll the remaining tape down smoothly on the board ensuring no bubbles are trapped. Use finger pressure to apply tape. The tape does NOT have to be pressed hard onto the board. The use of a small soft silicon squeegee is also helpful.

c. Verify tape has been laid down in the correct position. If not, remove tape. Reclean area. Repeat steps 1 and 2 above.

d. Wipe back of solar cell with Laboratory grade isopropyl alcohol and lint free cloth or towel. Ensure no flux remains from interconnector mounting.

e. With Exacto blade remove top protective covering on NuSil tape to expose the top adhesive. Since the solar cells do not flex, remove the complete top film covering from the tape.

f. Place one edge of solar cell on the same respective edge of exposed tape. Allow cell to softly lay down into required orientation ensuring interconnectors are aligned with respective solder points on solar board. Using a soft, non-scratching squeegee device or card, and starting in corner of the solar cell that made initial contact with the tape, slowly apply pressure to the cell moving towards the other side. THE GOAL IS TO ENSURE NO AIR BUBBLES GET TRAPPED UNDER THE CELL. Air bubbles under the cell will expand in vacuum tests and crack the cell.

g. Inspect the bond for completeness and lack of air bubbles. Use Exaco to trim any excess overhanging tape.

h. Repeat as required for other cells.

i. Solder top electrical connections from cell to board per method B above.

D. ELECTRICAL TEST

1. Place completed solar panel in lighted area. Verify cell voltage is within specifications. One ITJ cell should produce approximately 2.4 V under full sunlight.

2. Conduct test with EPS and FM430 as required to verify proper operation of complete Solar panel board.

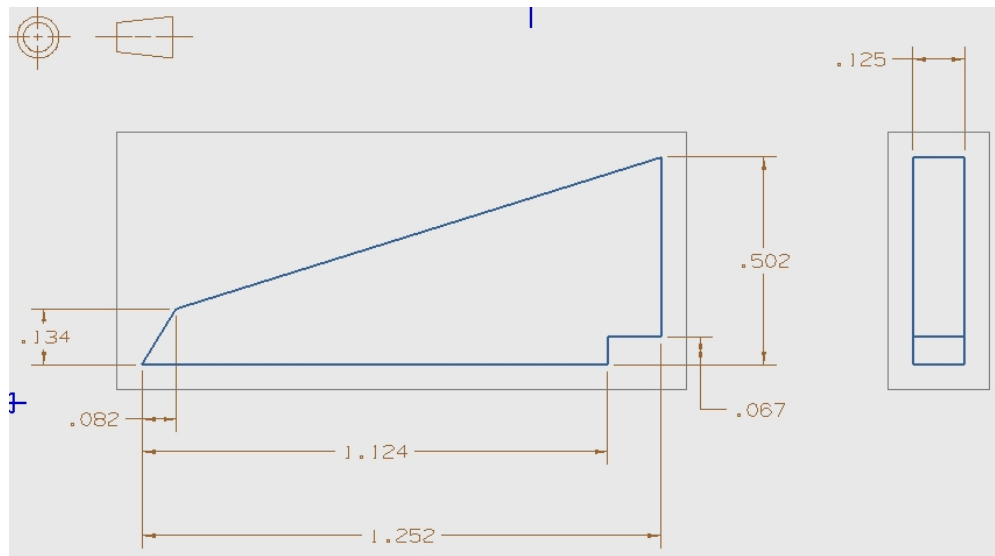


Figure 16. TASC Template

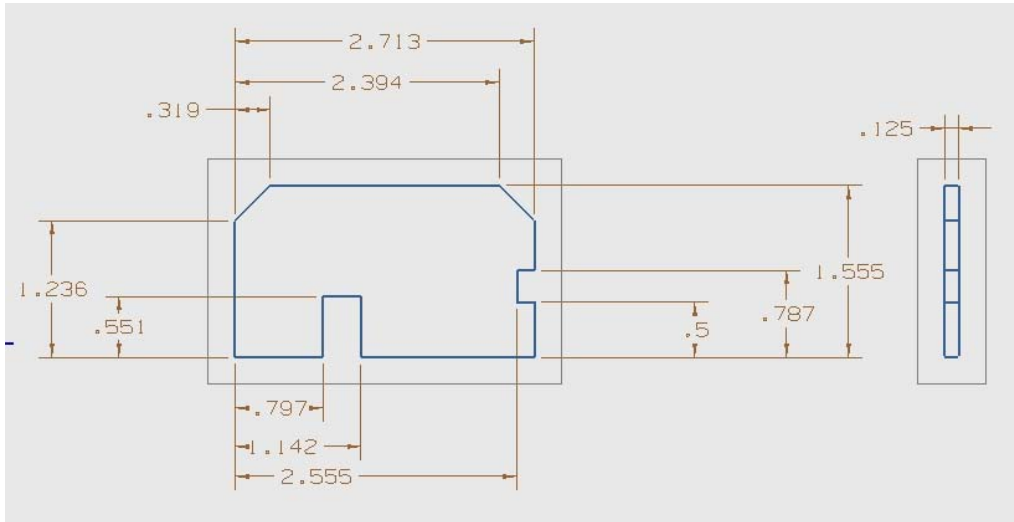


Figure 17. ITJ cell template

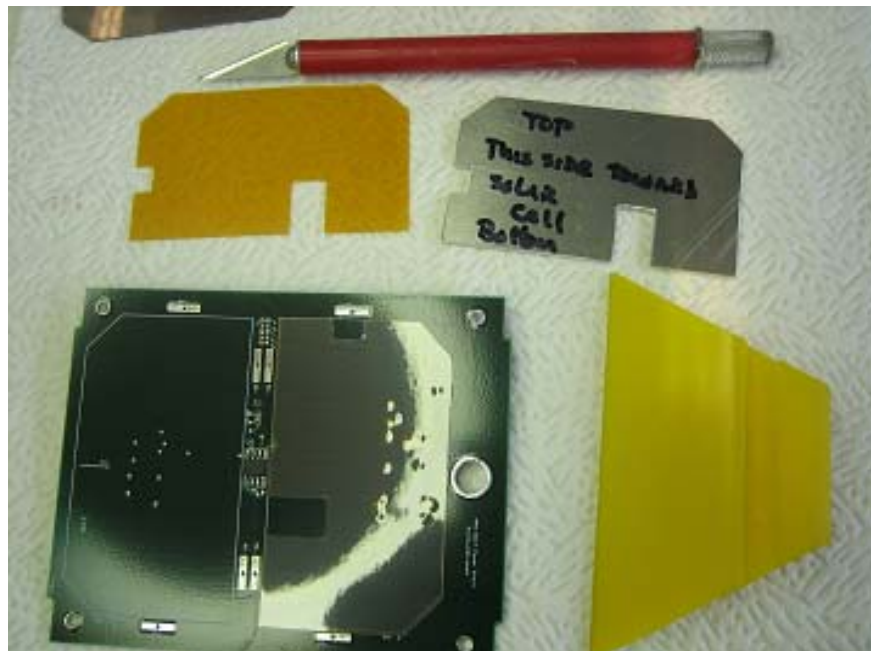


Figure 18. Solar cell application parts

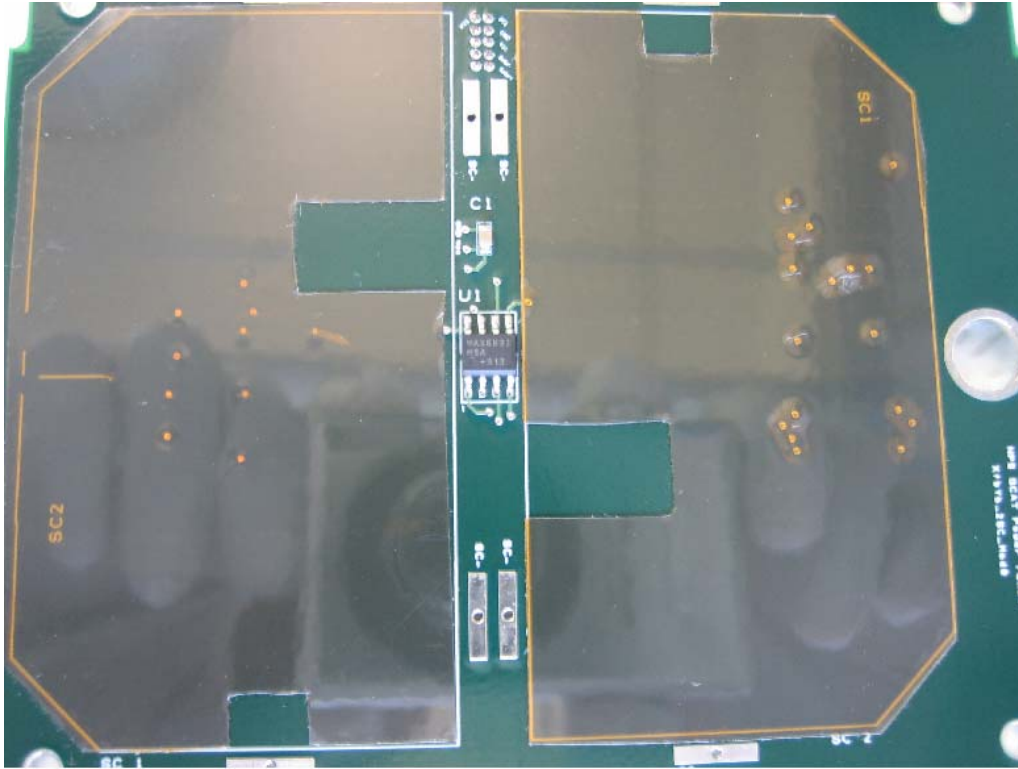


Figure 19. NuSil applied. Note bubbles on right side from Vias

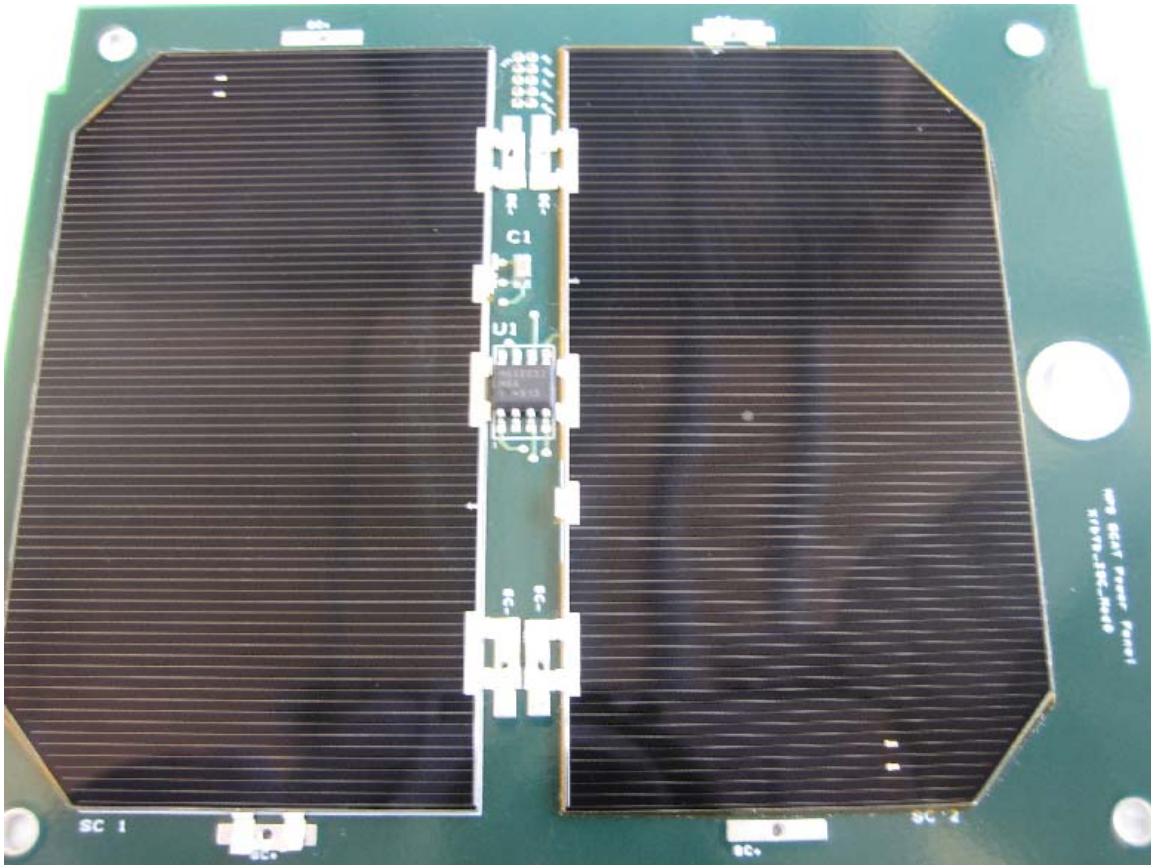


Figure 20. Complete panel. Cells applied with NuSil double-sided tape

APPENDIX D. CLYDE SPACE ELECTRICAL POWER SYSTEM (EPS) ACCEPTANCE TESTING

The following procedures were generated for testing and acceptance of the Clyde Space 1U EPS for use in the SCAT CubeSat project. It is designed to ensure EPS operation within design manufacture parameters. Readings that fall outside design specs should be investigated and discussed with manufacturer for resolution and replacement of unit.

A. SYSTEM INTRODUCTION

This document describes the Clyde Space EPS acceptance testing procedure for the NPS-SCAT CubeSat and NPS-SCAT++ satellites. The acceptance test will verify the EPS meets the documented specifications and can interface with the other satellite systems.

B. APPLICABLE DOCUMENTS

Test Requirements for Launch, Upper-Stage, and Space Vehicles. AEROSPACE REPORT NO. TR-2004(8583)-1 REV. A. 6 September 2006.

CubeSat Power System User Manual (CS-C1UM-01.DOC). Clyde Space, Glasgow, UK. 18 June 2007.

C. ACRONYMS

The following is a list of acronyms used in this document:

EPS	Electrical Power System
NPS	Naval Postgraduate School
SCAT	Solar Cell Array Tester

D. HANDLING PRECAUTIONS

Warning: A suitable battery load MUST be connected to EPS main battery bus (H2.41-44) before applying power to battery charge regulators (BCR) or severe damage can occur to the BCR, resulting in inoperable battery charging circuitry. With the battery daughter board connected, the pull pin switch must be closed (H2.41-44 to H2.33,34); otherwise damage will occur to the ceramic capacitors contained within the BCR regulators.

Warning: Battery board hex bolts used to hold battery board to EPS have live battery voltage on them. The upper left hand bolt (header connector oriented upward) contains battery positive voltage and should be protected to prevent shorting of battery or components. The other three hex bolts are battery ground.

All work should be performed with EPS located on a non-static producing and/or grounded work area.

Instruction Notes: instructions below will refer to Pull Pin (PPsw) and Separations switch (SEPSw). The PPsw is shut by connecting one pin between the EPS header pins H2.41-44 and H2.33,34. The SEPSw is shut by connecting one pin between EPS header pins H2.41-44 and H2.35-36. Figures 18 through 24 provide Clyde Space reference images and electrical documentation from Clyde Space reference documentation.

E. PARTS AND EQUIPMENT

1. Parts List

Clyde Space EPS Board Rev. C

Clyde Space Battery Daughter Board.

2. Equipment List

Programmable power supplies

Visual magnification device

Voltage and current measuring devices

I²C capable device for communication with EPS

Suitable jumper and connection wires compatible with EPS header pins.

Variable resistive load

F. EPS ACCEPTANCE PROCEDURE

1. Visual Inspections

A. Conduct a visual inspection of EPS and Battery board. Battery board should not be installed on EPS for visual inspections.

1. Conformal coating inspection. Inspect for areas that will require recoating, missing coating, chipping, flaking.

2. Component inspection. Component soldering quality. Cold welds. Missing components. Wires jumpers adequately secured to board. Header pins straight and not bent or missing. Solar cell connector quality and pin check.

2. Functionality Testing

a. Preparation

Conduct test with EPS in standalone mode, i.e. not connected to other components like the Pumpkin development board.

1. If not already attached, stack 1U battery board onto 1U EPS.

2. Ensure EPS battery is charged for testing. Refer to Clyde Space manual for proper charging method.

3. Measure and record battery voltage between pins H2.33,34 and H2.29-32. Voltage should be between 7.2 and 8.2 V for testing.

b. I²C setup

1. If the ability exists to use the I²C communications of the Clyde Space EPS, then it should be connected to allow the reading of EPS values and compare against externally measured values.

2. If using the FM430 processor for I²C communications, there are two nonfitted resistors that are required to be fitted to allow I²C communications. By default the jumpers come nonfitted. P3.3(H1.21) and SCL SYS(H1.43) must be connected. P3.1(H1.23) and SDA SYS(H1.41) must be connected. Connection can be made with any jumper.

3. I²C functionality will not work unless the SEPSw is shut. This will power up the EPS I²C function.

c. Quiescent-Parasitic EPS Load Test

1. This test will determine the parasitic loads on the battery due to the circuitry design of the EPS. BCR and Voltage regulator loads will be determined. A current meter will be used to simulate the PPsw.

2. Shut the PPsw by connection of the positive current lead to the battery bus (H2.41-44) negative lead to Battery positive terminal (H2.33,34). The EPS is now powered on. Measure the battery voltage and current. This is the no load power drawn by the three BCR of the EPS. The value should be no more than 2 mA.

3. Shut the SEPsw. The voltage regulators and the rest of the EPS circuits are now powered. Measure battery current and voltage. The no-load current should have risen to no more than 60 mA.

4. Open SEPsw and then open PPsw.

5. The BCR and no load currents in the complete EPS prototype were 1.1 mA @ 7.62 V and 49.6 mA @ 7.59 V respectively.

d. EPS Battery Charge Regulator (BCR) Testing

1. This will check the ability of the BCRs to actually charge the EPS battery. It is possible to test the EPS with a simulated solar cell via the instructions provided in the Clyde Space manual.

2. Testing BCRs with actual solar cell array. The BCR require a minimum voltage input of 3.5 V. This will require a minimum of two solar cells in series to meet the

minimum voltage input requirements. Battery voltage should not be fully charged to allow BCR to actually charge the battery.

a. Create a two cell series solar cell panel with an appropriate ability to connect to the EPS solar panel inputs SA1, SA2, or SA3. The solar panel should be able to produce a minimum of 0.4 W to overcome the 0.1 W parasitic losses of EPS BCRs. An estimate of 0.1 W per TASC can be used to create a small solar array. DO NOT CONNECT TO EPS WITHOUT PPsw SHUT.

b. Shut PPsw via current meter. EPS is now partially powered.

c. Measure Battery voltage and current. Current flow should be out of battery at no more than 2 mA.

d. Connect solar array to SA1. Apply adequate light to solar array to produce a voltage above the 3.5 V minimum input voltage.

e. Measure Battery voltage and current. Battery current should be flowing into battery. Battery voltage should be increasing based on charge current into battery and initial battery voltage. If there is no indication of battery charging the initial battery voltage may be too high. Discharge the battery via load placed on EPS 5 and 3.3 V output busses as discussed in later sections.

f. I²C measurements. Close SEPsw. I2C Bus activated. Use I²C to measure solar array and battery parameters. Compare with externally measure values.

g. Shift the solar array between SA2 and SA3 to verify charging capability operation of the three BCRs.

h. Remove solar arrays from EPS.

i. Open SEPsw then Open PPsw.

3. Optional: Testing BCRs with power supplies simulating solar arrays. Refer to Clyde Space manual for setup and connection of simulator.

a. Perform steps 2a-e above but with power supply simulating solar array.

b. Measurements of solar cell supplied power can be compared against input charge power to battery to determine BCR efficiency.

e. *EPS 5V and 3.3V Bus Load Testing*

1. The rated current capacity of the EPS 5 V and 3.3 V buses are 1.2 A and 1.0 A respectively. Testing will ensure the ability of the EPS to hold rated bus voltages with various resistive loads starting with 10 Ohm load and lowering the value until the buses fails to hold rated bus voltage.

2. Connect voltmeter to allow measurement of battery voltage(H2.33,34) to GND(H2.29-32).

3. Shut PPsw using Current meter. Connect Battery bus(H2.41-44) to Battery positive(H2.33,34).

4. Shut SEPsw. Jumper (H2.41-44) to (H2.35,36). EPS is now fully powered. I²C bus is now active.

5. Connect 10 Ohm resistive load to output of the 5 V bus (H2.25,26) to GND (H2.29-32). Connect meters to allow measurement of Load voltage and current.

6. Measure the following: Battery voltage, Battery current, 10 Ohm load voltage and current. The current should be in the 0.5 A range based on load. Use I²C to measure Battery parameters if available. EPS should be able to hold the 5 V bus at 5 V. Note: EPS I²C is unable to measure 5 V and 3.3 V bus parameters.

7. Shift the load to the 3.3 V bus (H2.27,28) and GND(H2.29-32).

8. Measure the following: Battery voltage, Battery current, 10 Ohm load voltage and current. The current should be in the 0.330 A range based on load. Use I²C to measure Battery parameters if available. EPS should be able to hold the 5 V bus at 5 V. Note: EPS I²C is unable to measure 5 V and 3.3 V bus parameters.

9. Repeat steps 5 through 8 as the load is slowly lowered until the EPS is unable to hold the rated voltage. Ensure both battery and load currents are recorded. It should match or be very close to rated current loads.

10. Open SEPsw then Open PPsw.

11. Compare the power supplied by 5 V bus and 3.3 V bus as compared to the power being drawn from the battery. The rated efficiency of the EPS 5 V and 3.3 V output buses was not given. The prototype EPS efficiency varied from 80% to as low as 60% when a bus was close to its current limits. For the 5 V bus, the prototype values were 5 V bus power

drawn was 2.31 W ($4.98 \text{ V} * 0.465 \text{ A}$). Battery power drawn 2.92 W ($7.19 \text{ V} * 0.407 \text{ A}$). Efficiency $2.31 \text{ W} / 2.92 \text{ W} * 100\% = 79\%$.

For 3.3 V bus, the prototype values were 3.3 V bus power drawn was 1.0 W ($3.28 \text{ v} * 0.306 \text{ A}$). Battery power drawn 1.42 W ($7.27 \text{ V} * 0.196 \text{ A}$). Efficiency $1.0 \text{ W} / 1.42 \text{ W} * 100\% = 70\%$. Tables 4 and 5 of Chapter III show the testing results of first Clyde Space EPS tested with above procedures.

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APPENDIX E. EPS DIAGRAM AND SCHEMATICS



Figure 21. Clyde Space 1U EPS (From Clyde Space)



Figure 22. Clyde Space EPS with 2 Cell LiPo Battery board attached (From Clyde Space)

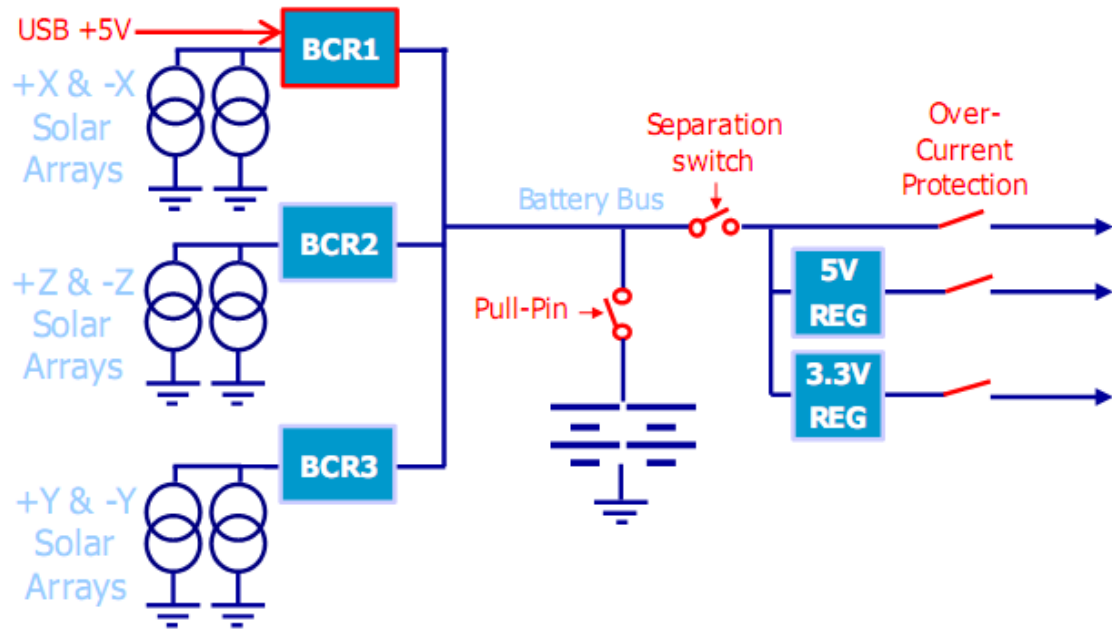


Figure 23. Clyde Space 1U EPS Block Diagram (From Clyde Space)

H2	2	4	6	8	10	12	14	16	18	20	22	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52
	1	3	5	7	9	11	13	15	17	19	21	23	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52
H1	2	4	6	8	10	12	14	16	18	20	22	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52
	1	3	5	7	9	11	13	15	17	19	21	23	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52

Figure 24. EPS Header Pin diagram (From Clyde Space)

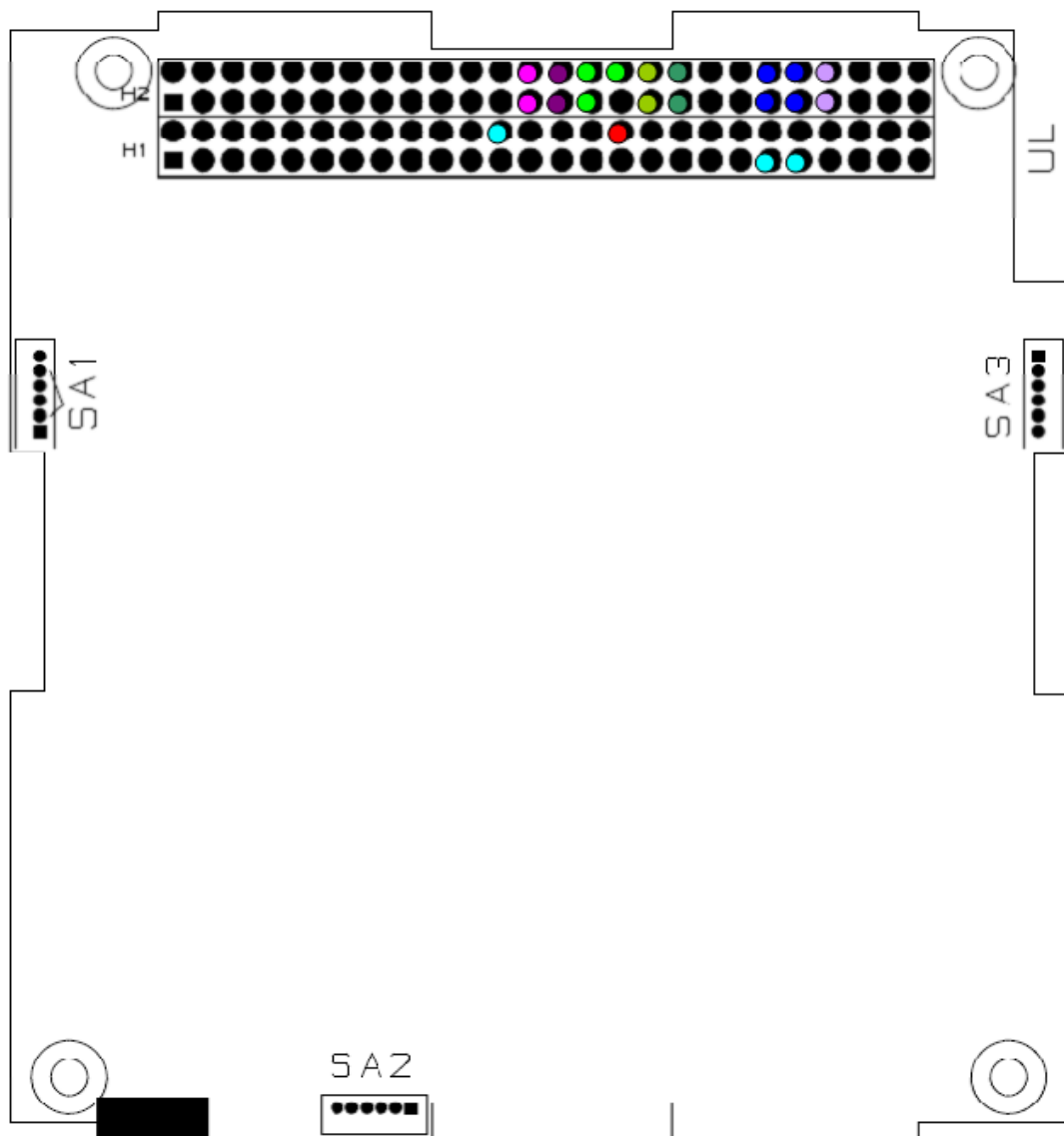


Figure 25. EPS Connector location layout (From Clyde Space)

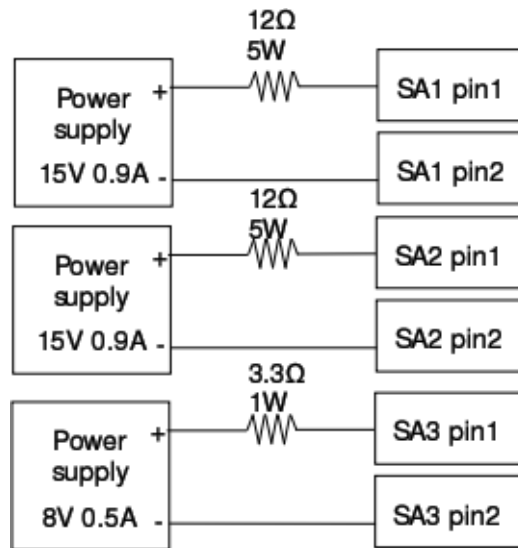


Figure 26. Clyde Space BCR Bench Test Setup with solar simulator (From Clyde Space)

PIN DESCRIPTIONS

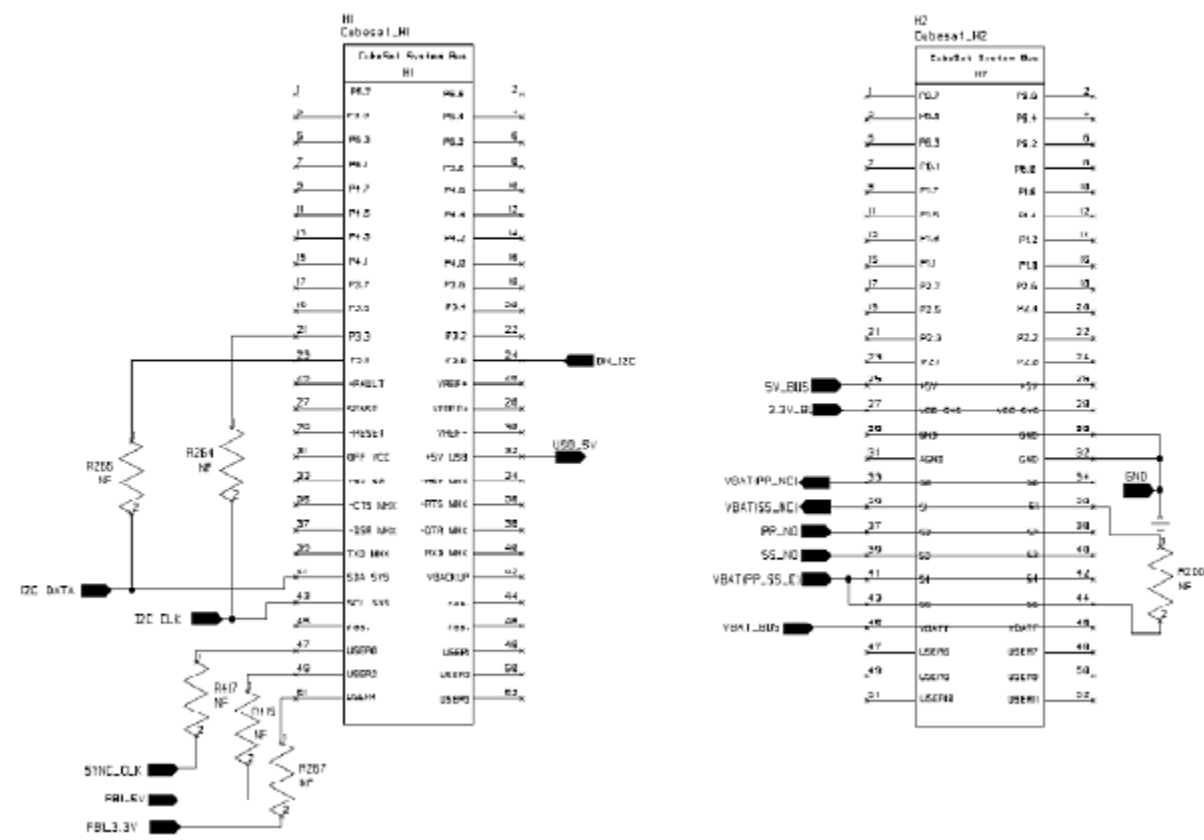


Figure 27. EPS Header 1 and 2 connections (From Clyde Space)

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APPENDIX F. MATLAB POWER SIMULATION CODE

A. MATLAB CODE

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
%      NAVAL POSTGRADUATE SCHOOL      %%
%      SPACE SYSTEMS ACADEMIC GROUP   %%
%      MONTEREY, CA                   %%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
%=====
%      THE NPS-SCAT CUBESAT           %
%=====

%Power budget NPS-SCAT

close all
clc
clear
% no = input('Enter number of orbit to evaluate:')
% ot = input('Enter orbit time (mins):')
% st = input('Enter Maximum Sun time (mins):')
% pg = input('Enter Average in Sun power generated (Watts):')
% bdc = input('Enter Beacon duty cycle (percent of total orbit time)(%):')
% N=no*ot %create the total of simulation minutes
% P = N:

% Power report is given in a 60 seconds time step
% M is equal to the number of minutes in the sun.
% N is equal to the number of total on orbit minutes for simulation
P = csvread('power_npsscscat_bcn14.csv',1,0);
[n,o]=size(P);
N=n;

L = csvread('link-budget_dorn_new.csv',1,1);
[M,b]=size(L);

%initialize link(i) vector to zeros N= number of minutes in the
%power_npsscscat file.
for i=1:N
    link(i)=0;
end

%M is the number of access as determined from the link-budget.csv file
% this sections set a 1 value for the link vector for all minutes/secs that
% access is possible with NPS.
for i=1:M
    for j=L(i,1):L(i,2)
        link(j)=1;
    end
end
```

```

end
end

%%%%%% LOADS in watts

% mpb - main processor board.(0.014W) Stby load included in EPS
% parasitic load.
mpb_stby = 0.0;
%   power up, comm data  0.1W/ 3.3V regulator efficiency 70%,
mpb_on = 0.014;

% EPS - Electrical Power board system
% parasitic losses of .3W due to voltage regulators
eps_on = 0.361;

% com - communication board power down (0.01W).
% Stby load included in EPS parasitic load.
com_stby = 0.0;
%   transmit data  4.0W/5v regulator efficiency 80%
com_on = 5.0;

% com - Beacon board
% bcn power down. (.01w) Stby load included in EPS parasitic load.
bcn_stby = 0.0;
% bcn transmit data (1.25W) 1.0/5v regulator efficiency 80%
% about .850w results in self sustaining load=generated
bcn_on = 1.25;

% sms - sms board
% power down. (0.067W) Stby load included in EPS parasitic load.
sms_stby = 0.0;
%   taking data  0.294W/5v regulator efficiency 80%
sms_on = 0.367;

% N is equal to the number of total on orbit minutes for simulation
% if link vector value is equal to
for i=1:N
    %if link vector value is not equal to zero (i.e. 1) then in a comms window
    %and everything comes on
    if link(i)~=0
        mpb(i)=mpb_on;
        com(i)=com_on;
    else
        mpb(i)=mpb_stby;
        com(i)=com_stby;
    end
    % if sat is in the sun then sms is on and taking IV curves.
    if P(i,3)==1
        sms(i)=sms_on;
    else
        sms(i)=sms_stby;
    end
end

```

```

%bcn transmit required
if P(i,4)==1
    bcn(i)=bcn_on;
else
    bcn(i)=bcn_stby;
end
% bcn(i)=bcn_on*(bdc/100) %bcn average watts consumed per minute of orbit.

load(i)=mpb(i)+com(i)+bcn(i)+sms(i)+eps_on; %power load at minute i.
generated_power(i)=P(i,2); %watts/min being generated at minute i.
end

for i=1:N
    generated_energy(i)=generated_power(i)/60; %watts per hour generated
end

%%%%%%%% capacity of the battery
%    1.25Ah * 8.4V = 10.5 Wh
cap_batt_start = 10.5;

%%%%%%%% EPS conversion efficiency = 100%
eff=0.9;

%%%%%%%% battery starts with 50% of its full capacity to allow charge/discharge process to be
shown visually.
cap_batt(1) = cap_batt_start*0.5;

for i=2:N
    cap_batt(i) = cap_batt(i-1)+eff*generated_energy(i)-load(i)/60;
    if cap_batt(i)>cap_batt_start
        cap_batt(i)=cap_batt_start;
    end
    cap_batt_percent(i-1) = (cap_batt(i-1)/cap_batt_start)*100;
end

%%%%%%%% plots

% Create figure
figure1 = figure('Name','NPS-SCAT Power Budget','Color',[1 1 1]);

subplot1 = subplot(2,1,1,'Parent',figure1,'YGrid','on','XGrid','on');
%xlim([80 240]);
box('on');
hold('all');
plot(load,'DisplayName','load','Parent',subplot1,'Color',[1 0 0]);
xlabel('Time [min]');
ylabel('Loads [W]');

subplot2 = subplot(2,1,2,'Parent',figure1,'YGrid','on','XGrid','on');
%xlim([80 240]);
box('on');
hold('all');
plot(cap_batt,'DisplayName','cap_batt','Parent',subplot2);

```



```

xlabel('Time [min]');
ylabel('BATTERY capacity [Wh]');

figure2 = figure('Name','NPS-SCAT Battery SOC','Color',[1 1 1]);

%plot3 = plot('Parent',figure2,'YGrid','on','XGrid','on');
box('on');
hold('all');
grid('on');
plot(cap_batt_percent,'DisplayName','cap_batt_percent',...
'Color',[0 1 0]);
xlabel('Time [min]');
ylabel('Battery state of charge [%]');

```

B. MATLAB INPUTS EXAMPLE: SCAT POWER, SOLAR INPUT, AND BEACON INPUTS

Time (EpMin)	Power (W)	SMS On	Bcn on
240	0.597	1	1
241	0.279	0	0
242	0	0	0
243	0	0	0
244	0	0	0
245	0	0	0
246	0	0	0
247	0	0	1
248	0	0	0
249	0	0	0
250	0	0	0
251	0	0	0
252	0	0	0
253	0	0	0
254	0	0	1
255	0	0	0
256	0	0	0
257	0	0	0
258	0	0	0
259	0	0	0
260	0	0	1
261	0	0	0
262	0	0	0
263	0	0	0
264	0	0	0
265	0	0	0
266	0	0	0
267	0	0	1
268	0	0	0
269	0	0	0
270	0	0	0
271	0	0	0
272	0	0	0
273	0	0	0
274	0	0	1
275	0.009	0	0
276	0.672	1	0
277	0.746	0	0
278	0.908	0	0
279	1.032	0	0
280	1.045	0	0
281	1.169	0	1
282	1.492	0	0
283	1.418	0	0
284	1.393	0	0
285	1.405	1	0

Table 8. Minutes 240 through 285 of SCAT orbit MATLAB input. Minutes 242 through 274 indicate SCAT in eclipse. Minutes 0 to 240 are SCAT 4 hour wait time.

C. SCAT ACCESS MATLAB INPUTS

Access	Start Time	Stop Time	SCAT Access Duration (sec)		
1	195	199	200		
2	682	685	206		
3	1682	1684	117		
4	3071	3074	204		
5	3558	3561	207		
6	4558	4560	89		
7	5947	5950	206		
8	6434	6437	207		
9	7434	7435	45		
10	7825	7826	73		
11	8823	8826	207		
12	9310	9313	205		
13	10700	10702	105		
14	11699	11702	206		
15	12185	12189	202		
16	13576	13578	128		
17	14574	14578	204		
18	15061	15065	197		
19	15965	15967	84		
20	16452	16454	146		
21	17450	17454	201		
22	17937	17940	190		

Table 9. SCAT to NPS access times MATLAB inputs

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